AC 2008-2364: HARVESTING OF LUNAR IRON: COMPETITIVE HANDS-ON LEARNING

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Harvesting of Lunar Iron: Competitive Hands-on Learning

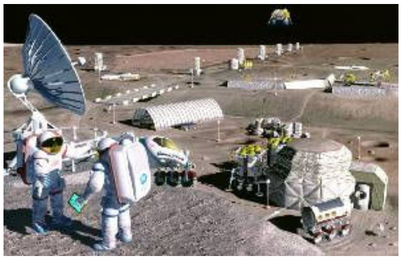
Abstract

Electromagnets can be used to harvest free iron from lunar soil, known as regolith. Iron is important to the US plans for a lunar outpost. It does not rust in space, making it an excellent construction material. Circumpolar railroad tracks would allow a slowly-moving train to follow the sun, making agriculture possible, and enabling continuous operation of factories producing solar cells and oxygen for life support and propulsion. Designing an iron harvesting apparatus for the unique lunar environment requires that students re-think tacit assumptions about how things work.

Within the context of a 33-student summer program, two college interns supervised nine high school upperclassmen in an eight week project to design, test, and evaluate a lunar iron harvester. Under the guidance of high school teachers, a research engineer outlined the constraints and parameters for the project. The college interns developed performance metrics, and the teachers established the framework for the competition. Three teams of three students developed their designs, which were reviewed by professional engineers prior to fabrication. A separate team performed research on the properties of lunar soil and prepared a test bed containing 150 kg of simulated regolith.

One team identified a novel means to multiply electromagnet force using a recently-issued patent, creating great excitement between the teams and spurring them all to excel. Electromagnets were fabricated in the Packer Engineering shop, then operated by the students in a standardized competition format. Wearing proper protective gear, each team tested their device to determine the amount of free iron extracted from the regolith simulant. Performance was measured in mass of iron harvested per device mass, yielding surprising results, and powerful insights for the students. Results were published in a local newspaper. In this paper, we describe how this hands-on project fits within an overarching philosophy for engineering education within a paid summer intern program.

Introduction



Since before man first landed on the moon in 1969, there have hopes and plans for settlement. In his 2004 State of the Union Address, President Bush announced a new vision which includes “a foothold on the moon” which will “prepare for journeys to the worlds beyond our own”. With launch costs to the moon of $100,000 per kilogram, a major focus at NASA is learning to “live off the land” when we return to the moon. The technical term for this is in situ resource utilization (IRSU), and includes manufacture or extraction of useful raw materials and consumables needed for human habitation and rocket transportation. Building and structural materials are current objectives for ISRU, owing to their high mass. In this paper, we review the extraction of iron from simulated lunar soil using devices designed, constructed, and tested by student researchers.

Nearly the entire lunar surface is covered with a gritty dust called regolith. This sand-like substance has been created by billions of years of meteorite bombardment, and covers the lunar bedrock to depths ranging from 0.5 to 4 meters, except on cliff walls. The topmost layer is extremely fine, with an average particle size of 0.07 mm (see image to right), and a porosity of about 37%. With increasing depth, regolith becomes more compacted and contains larger aggregates.

The elemental composition of regolith is shown in Figure 1. Note that iron comprises about 1/8th of the soil by weight, mostly in the form of ferric oxide, ilmenite and olivine where it is strongly bound to oxygen. However, there is a small amount of free iron present in regolith. Free iron is likely deposited by impacts from iron-nickel and stony-iron meteorites, and consists of loose iron particles, as well as iron amalgamated with nickel, and iron filings embedded in agglomerates of other minerals. The amount of free iron varies by location on the moon, ranging from 0.1% to 0.5% by weight. It is this loose, free iron that can hopefully be harvested efficiently.

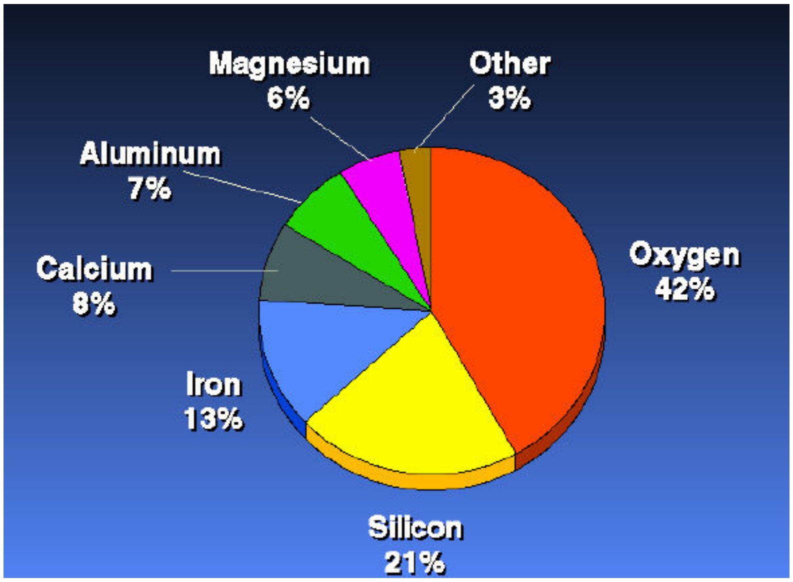


Figure 1. Elemental composition of lunar regolith by weight.

Extracted free iron can be used as a structural material on the moon. Lunar iron is expected to be stronger than terrestrial iron because of the much lower carbon content (less than 280 ppm). Unlike the earth environment where atmospheric oxygen and moisture cause iron to rust, the moon is devoid of both. And because lunar gravity is 1/6th that of earth, iron is an ideal material.

Design and Fabrication

Each summer, Packer Engineering hosts over 30 students, half of which are high school upperclassmen. The high school intern program combines both hands-on practical experience and a wide exposure to a range of engineering topics. College interns, comprising the other half of the student workforce, divide their time between billable hours working for engineers and conducting their own research projects. In the summer of 2007, 9 of the high school interns participated in a competitive setting to design, build and test a lunar iron harvester. Preliminary technical information was provided to them and they were guided through the process by two college interns managed the project.

The two design activities proceeded in parallel. The first was the design of the lunar regolith simulant. Researching the composition of lunar soil, three students used terrestrial analogue materials to reproduce those properties of regolith most pertinent to the test. Density, porosity and iron content were deemed most critical. Silica is the most abundant mineral on the lunar surface, and using the close replica of commercially-available play sand, the team conducted research into ways to mimic the unique properties of regolith. They discovered perlite, a porous volcanic glass with a very low specific gravity (1.1 g/cm^3). Porosity was measured using the water displacement method, in which a given volume of material is added to a graduated cylinder, and then measured amounts of water are added to fill the empty spaces. By combining 89.7% sand, sifted through a 4.0 mm grid, 10% perlite, and 0.3% free iron, the simulant team created a mixture with a specific gravity of 1.6, a porosity of 33%, and a free iron content in the middle of the range found on the moon. This was deemed a reasonable tradeoff to lunar soil at 1.71-1.89 specific gravity and porosity of 37%.

When iron filings were added to the play sand and perlite, the simulant team conducted electromagnet tests to verify that the iron content was correct. Instead, they found their calculations different by 0.2% from measurements taken with a triple beam balance. Testing as-purchased play sand revealed 0.2% free iron. The first batch was discarded and all-purpose sand was used instead. Validation testing confirmed the calculations.

The simulant team also designed a test rig for the electromagnet teams. A rectangular clear plastic container was built on-site having dimensions of 0.25 m wide, by 1.5 m long, and 0.55 m depth (see figure 2). Special adhesives were used to avoid metal fasteners. An overhead crane was in the initialplans to sweep the competing electromagnets across the 1.5 meter track; however the crane speed proved too variable, so a timed, hand-held sweep was used instead, with results averaged over three runs.

Figure 2. Preparation of simulated lunar regolith with free iron, with simulant tank pictured.

The electromagnet teams were given several design constraints:

- Available power limited by voltage less than 50 volts and current less than 30 amperes
- designs must pass a peer review, including at least 1 licensed professional engineer
- maximize the mass of iron harvested by ratio to the electromagnet mass.

Although all high school interns possessed a passing familiarity with electromagnets, a lack of in-depth understanding generated a surprising amount of variation between the three teams. The design processes, and the reasoning behind them, are instructive as to how the students approached this problem.

Team MagMiners

The initial design was a "tuna can" with the aim of maximizing surface area versus weight. Images of fringing fields for short electromagnets [6] convinced the MagMiners to find a different approach. Their investigation led the team to a recent patent (US 6,246,561) to Flynn, teaching a method of multiply the force of an electromagnet by a judicious arrangement of multiple permanent magnets within a special electromagnet configuration. Although the MagMiners did not win the competition as constrained, they picked up the greatest mass of iron, and their apparatus exceeded the winning teams' ratio of iron harvested to power consumed by 66%. Also, in a dramatic illustration of the Flynn approach, the MagMiners hoisted a 2 meter steel I-beam from the floor using the same constraints on voltage and current.

The Riddlers

This design consisted of three iron cores each having 3 layers of wire wrapping. The Riddlers used a heavier gage wire than the other teams, to reduce resistance. The Riddlers design used just 50% as much current as the other two teams, picking up an equivalent mass. However, the heavy iron cores cost them heavily on the mass efficiency, and they finished in last place.

Team GOAT

The winning team threw out several design choices. The first failed due to the fine gage wire used, which could not be reliably wound or the 500 meters length required. Electrical resistance was also expected to be a problem. From research into magnet field lines, they also rejected a large area core due to the low average magnetic field across the face. Team GOAT then packed 6 large and 10 small coils into a 0.25 wide free iron sweeper, with an iron plate facing the regolith simulant (see Figure 3). Preliminary testing suggested the iron plate diffused the field too much, and it was replaced with a sheet of plastic.

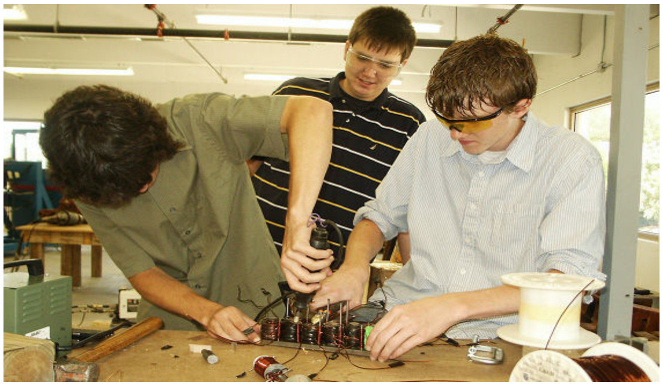


Figure 3. Electromagnet team fabricating their design.

Testing

The final testing was conducted in the high bay area, with the tank of regolith simulant mounted on a skid near the power supply. Each student wore protective goggles, steel-toed footwear, and dry leather gloves. A class C fire extinguisher was placed near the power supply, and one student was responsible to either pull the plug or operate the extinguisher as needed. College intern managers oversaw safety practices, and the high school intern program teacher-coordinators were also present. A news crew from a local publication attended, interviewing people and taking photographs.

Each electromagnet was swept across the surface of the simulant tank manually, recording the voltage and current levels. The sweep was timed to be 20 seconds, with a 1 second tolerance. If too short or too long, the trial was repeated. Following the sweep, power was removed, the electromagnet was tapped to release the iron, and the iron filings were weighed with a triple balance scale. Between tests, iron filings were replaced in the simulant tank, and mixed in manually using a garden trowel. Table 1 shows the results of the testing. Efficiency is the ratio of iron harvested to electromagnet weight, expressed as a percentage.

Place	Efficiency	Magnet Mass	Iron Mass	Current	Team
First	.1504%	2041g	3.07g	29A	Group Goat
Second	.1176%	5670g	6.67g	28A	MagMiners
Third	.0169%	20638g	3.49g	14A	The Riddlers

Table 1. Test results of simulated lunar iron harvesting.

The competitive format motivated the students to watch closely as rival teams were tested. Several insights were discovered by the students during the testing. When the power was switched off and the iron filings released the formed piles clustered at the periphery of the electromagnet cores (Figure 4, right image is thresholded and converted to 8-bit grayscale). Once observed on the GOAT design, other teams noticed a similar effect in their own designs. This caused a general consensus that a multitude of small cores may give superior results. A second discovery related to the effect of static electricity. The extremely porous Perlite beads became attracted to non-conductive surfaces, possibly attenuating the magnetic field by placing a barrier between the on the electromagnet apparatuses and the surface of the lunar simulant.

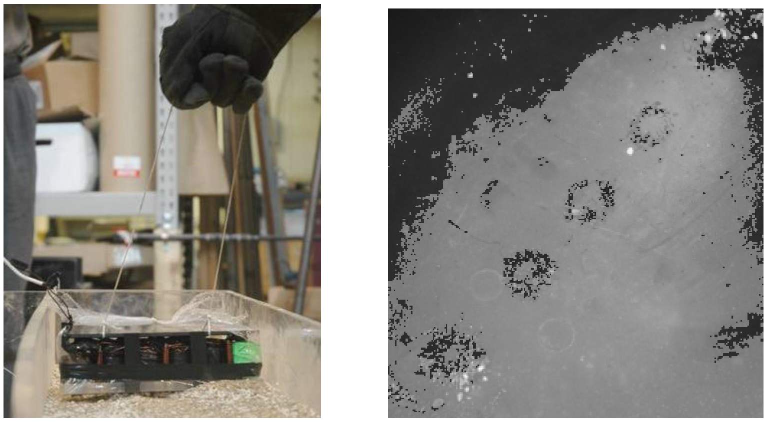


Figure 4. Electromagnet being swept (left) and iron filing pattern (right, thresholded).

Summary

Dubbed "Project Moonraker" by the student teams, this work exemplified the philosophy of the summer intern program. The Moonraker project possessed a relevance with which the students could identify. By providing very little material at the onset, each team followed a path of discovery and insight which was largely self-directed. In their own way, each team found a way in which their design excelled: GOAT won the competition by the criterion metric; MagMiners collected the greatest mass by a factor of two; and The Riddlers harvested the same amount of iron as GOAT but with half the current draw. Following this competition, one student is now pursuing sponsored research into magnets and coils being used in a self-powered shot counter – an odometer for military rifles, which indicates when a firearm is ready for maintenance. Among the student participants, one is now enrolled as a Nuclear Engineer, two are Electrical Engineering students, several are in Mechanical Engineering, and another will next year be enrolled as a Biomedical Engineer. The interest of a local newspaper, plus the competitive spirit of these students, imbued the final competition with excitement. Insights gained as the test results were tabulated appeared to leave these nascent engineering students with an intrinsic motivation to improve their performance – a valuable quality in our future engineering workforce.

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