SPACE RESOURCES AT SCALE: EXTRACTION AND PROCESSING 100MT OF METALS FROM THE MOON. E. A. Scott[1], D. Leger[2], P. E. Corwin[1], M. C. Sissman[1]. [1]Center for Space Resources, Colorado School of Mines, 1310 Maple St., GRL 234, Golden, CO 80401; eascott@mines.edu; pecorwin@mines.edu; mcsissman@mines.edu. [2]European Space Agency, Linder Hoehe, 51147 Köln, Germany; dorian.dleger@gmail.com.

Introduction: Space resources are the key to expanding humanity's presence into space. Learning to live off the land in space is the method by which humans will go from the flags-and-footprints space exploration model of the Apollo era to a sustainable, expansive human presence in space.

Although we are now just at the dawn of the space resources age, the time is right to consider how the technologies, processes, and sustainability considerations in development today can scale up to meet the needs of a full cislunar economy.

In August of 2021, the Planetary Sunshade Foundation, in collaboration with the Center for Space Resources at the Colorado School of Mines, hosted a workshop to address the use of space resources at the 100MT (megatonne, or millions of metric tonnes) scale. The purpose of this paper is to present the findings from the workshop's lunar resource extraction and processing group, as well as document a roundtable discussion on sustainable lunar resource development. Full workshop results can be found in [1].

Lunar Resource Extraction and Processing: The most abundant resource on the surface of the Moon is regolith. Regolith is the layer of unconsolidated rocky material, from dust to boulders, that covers bedrock. It is composed of silicate minerals and differs in composition between the older highlands material and the newer, volcanic mare material. Highlands regolith is relatively high in aluminum (about 13wt%), while regolith in the maria is higher in iron (about 15wt%) and titanium (up to 5wt%) [2]. Silicon accounts for about 21wt% of the regolith, but is higher in certain areas, such as the Gruithuisen Domes. These elements are tightly bonded with oxygen and other elements to form the silicate minerals that comprise lunar regolith.

Due to the Moon's lack of recent geologic activity, it did not experience the processes that concentrate minerals and elements into high-grade ores like the Earth did. Although certain metals are more abundant in the highlands or in the maria, extracting metals will simply be a matter of processing large quantities of bulk regolith. One benefit of this fact of lunar geology is that it essentially eliminates the need for prospecting; from Apollo samples and remote sensing data, we already know enough about the materials in lunar regolith to begin extraction and processing as soon as the technologies to do so are ready.

Although the composition of regolith varies between the highlands and maria, all major metallic elements (Al, Si, Fe, and Ti) are present in both types of regolith. As such, single-stream processing of bulk regolith could be used to extract different types of metals from the same bulk material. Heavy metals such as iron could be used to build up extraction and manufacturing capabilities on the lunar surface, while lighter metals such as aluminum and titanium could be moved off the lunar surface for use in orbital manufacturing. One significant trade study to be performed is whether it makes sense, at the 100MT scale, to have multiple extraction sites that specialize in specific elements, or whether single-stream processing of suboptimal bulk regolith at a single location is more efficient. While specialized processing methods are likely more efficient, having multiple launch locations to move materials off the lunar surface or transporting materials over long distances may negate that benefit. Single site operations may also enable economies of scale.

The production chain for metallic elements requires five steps: excavation of bulk regolith, transportation to a processing station, beneficiation of the regolith to enrich it, a reactor to break the metal-oxide bonds, and a high temperature separation step to extract the desired metal from other metals. There are different technology options available for each step of the process. For example, breaking the metal-oxide bonds could be done with a carbothermal reactor, a hydrogen reduction reactor, or molten salt electrolysis [3].

Workshop attendees identified iron as the first metal that will be needed to bootstrap mining capabilities on the Moon. Lunar iron could be used to produce larger, heavier extraction equipment for subsequent use in extraction of aluminum and titanium, launch facilities to move materials off the surface, and structures to house human workers.

Workshop attendees produced preliminary calculations to achieve an order-of-magnitude estimate of the regolith mass required to mine 100MT of iron. Analysis began with bulk regolith containing 10vol% ilmenite ($FeTiO_3$), which is a common oxide mineral in mare basalts. Beneficiation of the regolith could be accomplished with electrostatic separation, which could yield approximately 45% recovery of ilmenite with 67% ore purity [4]. Attendees then assumed that if 100% of the iron-oxide in ilmenite was successfully reduced in a redox reactor, and 95% of the resulting iron was recuperated by temperature-based separation, the mass of recoverable iron would be 1.6% of the mass of regolith brought into the processing system. Based on this finding, to produce 100MT of iron, 6,250MT of bulk regolith is required. Assuming that only the top 10m of regolith is excavated, this results in a mine size of 373km^2, or a square 19km on a side.

Similar calculations were performed for aluminum and silicon, with simpler assumptions. For aluminum, attendees assumed highlands regolith with 30wt% aluminum oxide (Al_2O_3). Assuming 100% recovery of aluminum from the regolith, a mine size of about 42km^2, or 6.5km on a side, is required to produce 100MT of aluminum if the top 10m of regolith are excavated. For silicon extraction, attendees assumed that regolith from the Gruithuisen Domes, at about 63wt% silicon oxide (SiO_2), was used. Assuming 100% recovery of silicon, 100MT of silicon can be extracted from a mine 22.6km^2, or 4.75km on a side.

Although substantial additional work remains to fully characterize the volume of regolith needed to produce 100MT of metal, these calculations provide a rough order-of-magnitude estimate of the potential size of regolith mines. A terrestrial comparison can be drawn to Florida's phosphate mines, which cover approximately 5,260 km^2 in central Florida [5].

Sustainable Space Resources Development: The workshop also included a roundtable discussion on sustainable space resources development. Humans have been poor stewards of Earth's environment, but we have a chance to do better in space if we consider sustainability from the outset. But what does sustainability mean for space? In terrestrial resource extraction, we consider remediation and sustainability to mean that life can return to the area after resources are extracted, but what does that mean for the Moon?

Humans have a cultural connection to the Moon; it is visible from everywhere on Earth and is considered sacred by many. Would large-scale resource extraction "deface" it? Even at the hundred megatonne scale, it's unlikely that extraction activities would be visible from the Earth without a high-powered telescope; however, even though Mt. Everest is not visible for most people living on Earth, many are nonetheless upset by images showing pollution and environmental devastation caused by human tourists, and it would likely be similar with images showing destructive lunar mining.

In modern terrestrial mining, remediation and end-of-life planning are part of the initial planning of a mine and are determined before the mine is even established. This is a good model to follow for space mining. As we start to plan for large-scale lunar mining, we should also plan for how the environment should look after we're done. What should be done with old equipment? How should mine tailings be dealt with? To what extent should the environment be restored to its original form when the return of native life need not be considered? Questions such as these should be considered by academics, industry, governments, and cultural representatives alongside technical matters for mining on the Moon.

Conclusions: Sustainability in space exploration can have two meanings. The first is sustaining human activity in space with less need for resupply from Earth. The more resources we can draw from outside Earth's gravity well, the more self-sufficient human space explorers can be. Though there is substantial additional work needed to fully characterize lunar regolith mining operations, preliminary calculations from the workshop show that the scale could be commensurate with terrestrial mines. The second meaning of sustainability is the reduction of environmental impacts of space resource extraction. Lunar mining engineers can use modern terrestrial mining best practices and work with academics, governments, and cultural representatives to determine how best to sustainably expand our presence into the solar system.

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References:

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