Volatile Extraction and *In Situ* Resource Utilization for the Moon applied to Near Earth Objects

Dr. Eric Cardiff
NASA GSFC

Lunar Exploration Analysis Group
October 24th, 2012

ISRU Techniques on the Moon

Most development has focused primarily on the production of oxygen.

- Solid Gas Interaction:
  - Reduction mechanism (**H_2**, C, CO, CH_4, H_2S, Cl_2) -> RESOLVE / PILOT
  - Fluorination replacement
  - Carbo-chlorination.
- Molten Processes:
  - Molten Electrolysis (fluxed melting)
  - Molten reduction (carbothermal, Li reduction)
  - Oxygen benefication (oxidation and complete reduction)
- **Pyrolysis**:
  - Vacuum or Vapor phase
  - Plasma (10,000 C) separation, or reduction
- Acid Dissolution

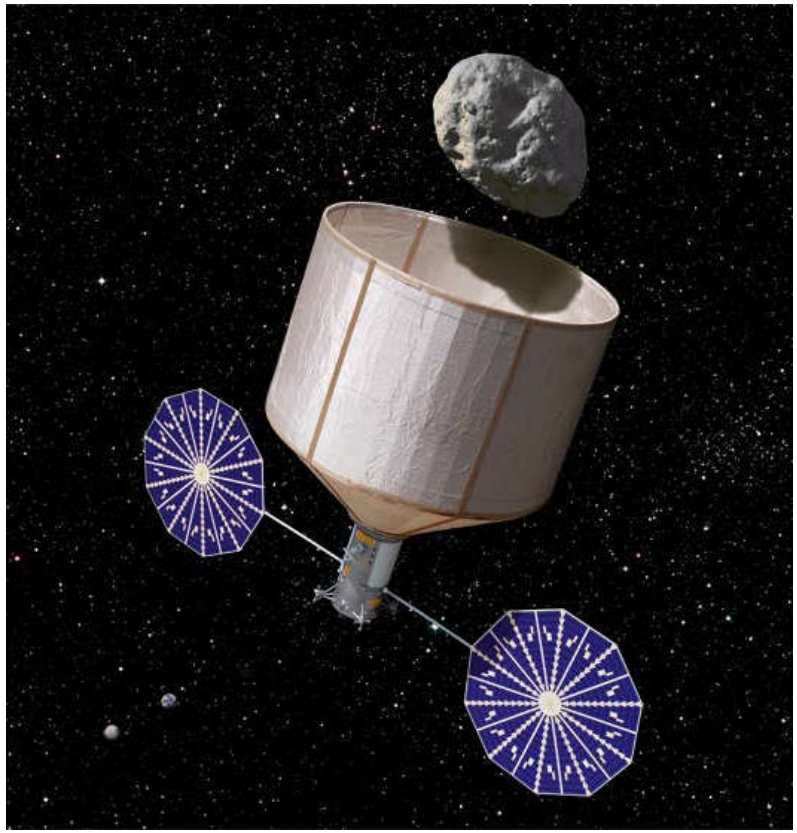
The extraction of water has focused primarily on accessing the water in the cold traps, or surface adhered water in the regolith.

Metals extraction requires significant processing, and for similar source materials as the oxygen. Metal oxides are the best source of oxygen.

What is needed for the flexible path?

- Technique
  - We either need one technique that fits all or multiple techniques that match the targets.
  - ISRU on Mars is technologically too far removed from the Moon and NEAs to work in common.
- Beneficiation
  - Many of the lunar beneficiation techniques require gravity (or magnetism).
- Reaction stock
  - The more reaction stock is required, the lower the process yield, and higher the cost.
- Energy
  - There is potentially more power available for NEAs (90 vs 0 degree incident sunlight). The final parking orbit and attitude are critical.
  - Because of the technological difficulty and significant propellant cost to maintain attitude, it will be easier to co-orbit, and not be attached to the asteroid.

Feasibility of asteroid capture



(Image Credit: Rick Sternbach / KISS)

- Asteroid Retrieval Feasibility Study, 2 April 2012, Keck Institute for Space Studies presents a feasible mission design ($2.6B).
- Size variability and density variability lead to bringing back a wide range of mass, between 200 and 1000 t, nominally 500 t for a 7m .
- Planetary Resources also has plans for a series of Arkyd spacecraft to detect, fly by, rendezvous with, and eventually mine a NEA.

Resources on the NEAs

Resources are highly unpredictable, depending on the type of NEA, and it is difficult to determine, outside of spectroscopic techniques (which only give surface composition) and direct sampling.

- Certain types are highly enriched in volatiles, and/or metals.
- Carbonaceous C-type asteroid can contain 40% volatiles (half water), ~20% metals (mostly iron, with some nickel and cobalt), and 40% silicates (similar to lunar regolith).

Strategies for development include:

- Prospecting and tailoring the ISRU to the target.
- Capture the most easily accessible target, and develop a general ISRU technique to exploit it.

Evaluation of ISRU on NEAs

- Most of the NEAs appear to possess enriched volatiles that are relatively easily extracted with temperature.
  - Important to measure these volatiles for scientific purposes with instruments like VAPOR/RESOLVE.
- Over 90% of NEAs are stony bodies (chondrites and achondrites) rich in volatiles.
  - To fully exploit this, one should use a technique that works on silicate chemistry to access the primary materials.

Hydrogen Reduction

- The technique uses hydrogen to reduce ilmenite or other feedstocks to produce water.

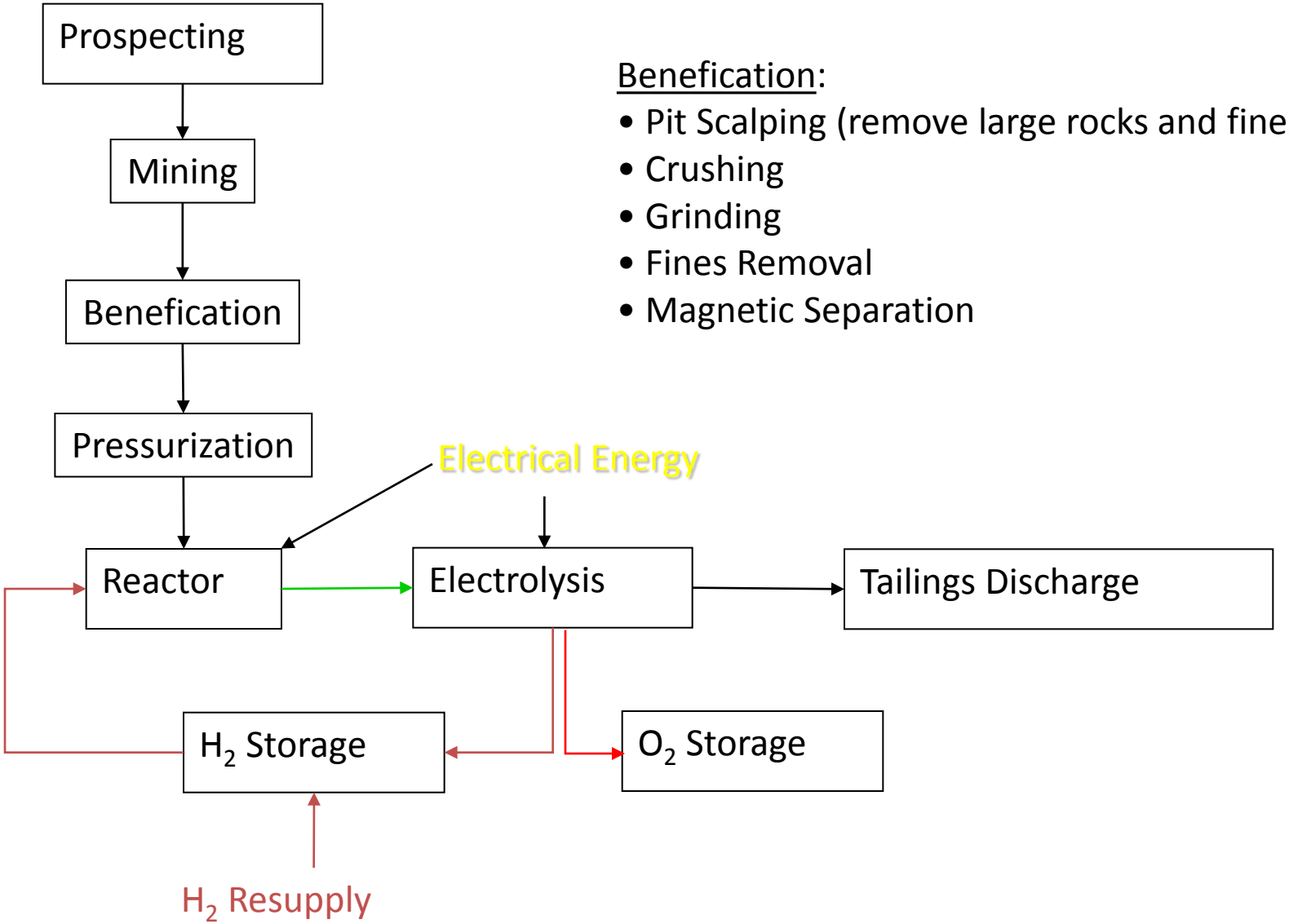
$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$

- This water can then be electrolyzed to recycle the hydrogen.

$$H_2O \xrightarrow{\text{electrolysis}} H_2 + \tfrac{1}{2}O_2$$

- The reaction occurs in a fluidized bed reactor at pressure.

Hydrogen Reduction



Benefication:

- Pit Scalping (remove large rocks and fines)
- Crushing
- Grinding
- Fines Removal
- Magnetic Separation

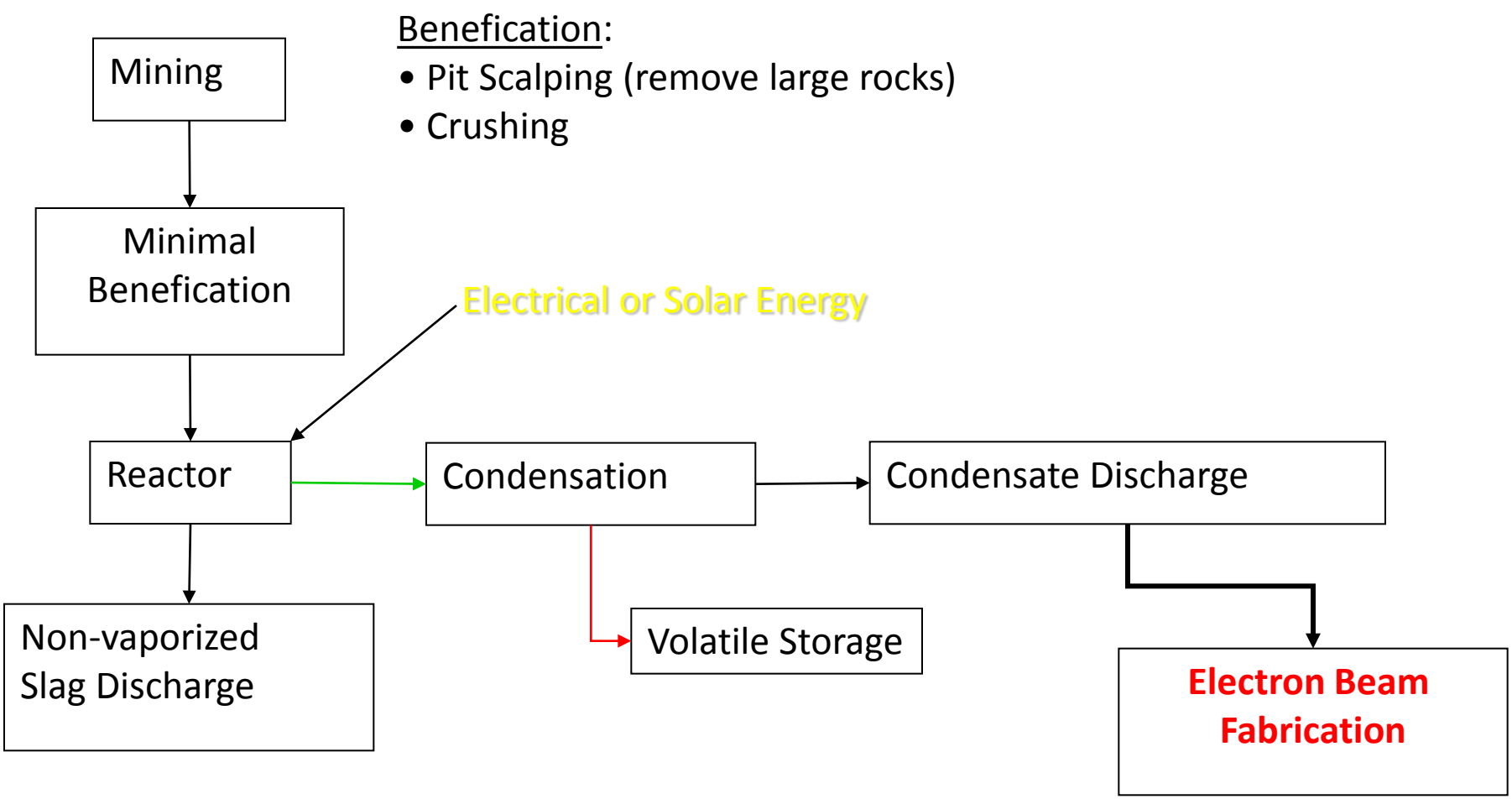
Vacuum Pyrolysis

- Vacuum pyrolysis is based on the vaporization reaction of metal oxides that simultaneously reduces the oxide and produces O_2.

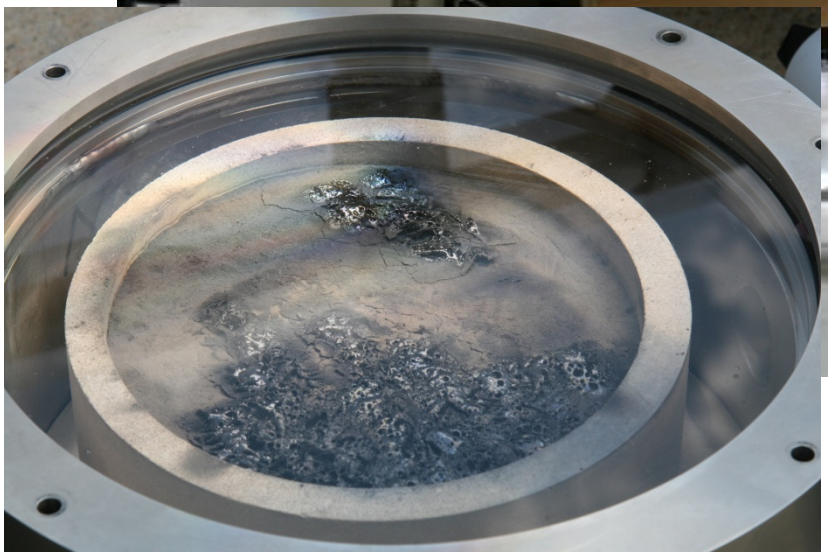
$$SiO_{2(s)} \rightarrow SiO_{(g)} + \frac{1}{2}O_{2(g)}$$

- It works on nearly all oxidized feedstock.
- The reduced oxide is condensed out of the low-pressure gas as the gasses cool.
- Vacuum pyrolysis has a high potential efficiency (up to 26% depending on the source material).
- The process requires no imported chemicals/consumables.
- Can produce metallic byproducts from the condensation.

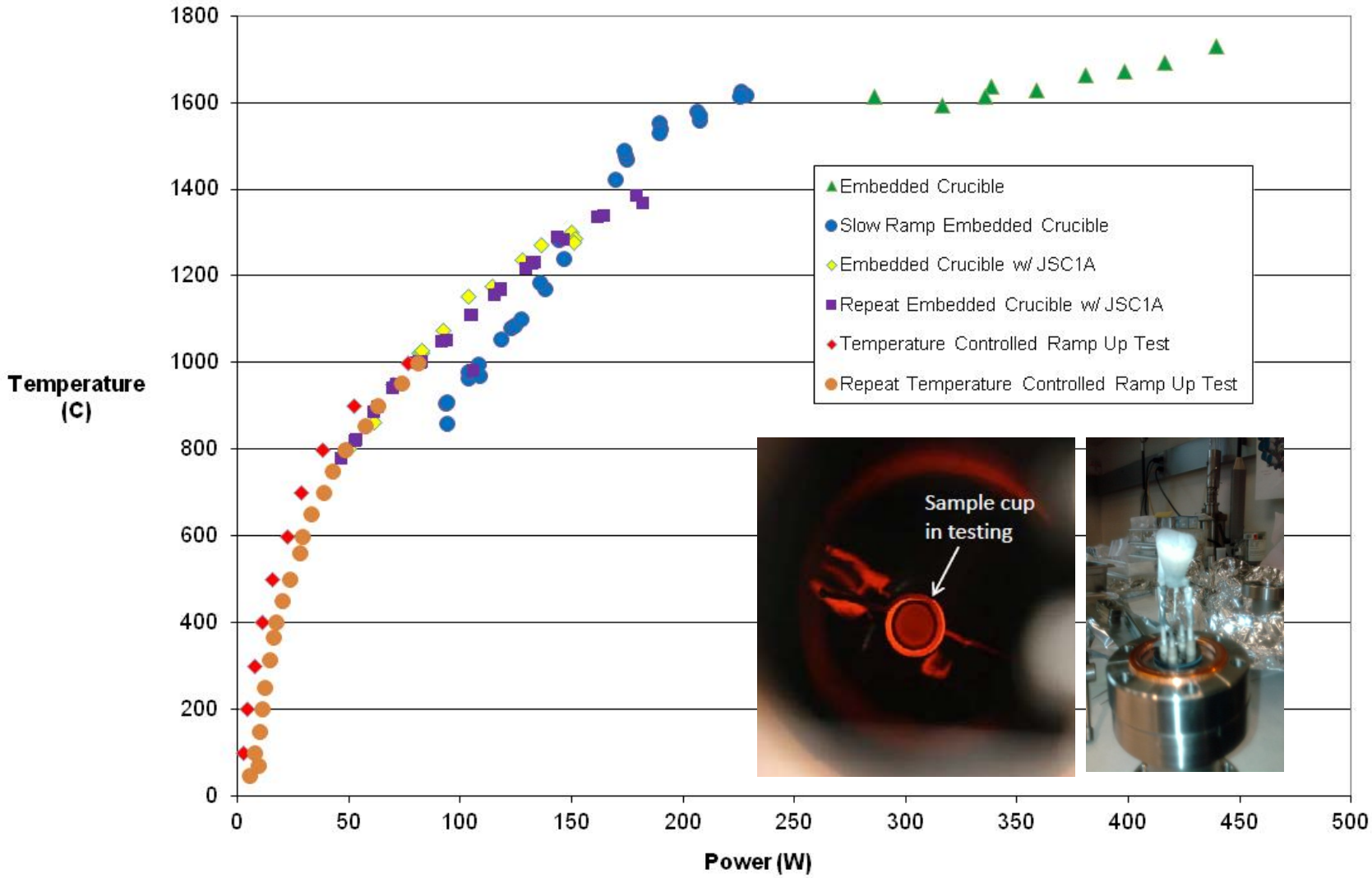
Vacuum Pyrolysis



Direct Solar Vacuum Pyrolysis SOA



Resistive Vacuum Pyrolysis SOA



All development by the VAPoR team

Scaling with direct solar heating

- High temperature operation with direct solar heating has been problematic. Vacuum enclosure on Earth do not handle high temperatures and solar flux well.
  - It is still possible on an NEA with a phased extraction
    - a contained process for “low” temperature volatiles
    - an open process for high temperature metal purification
- Current production rate is 7.5 g/min with a 1 m^2 Fresnel lens.
- Scaling up to a 100 m^2 lens allows a processing rate of 0.75 kg /min, or ~1 t / day
  - A volatile production rate of 0.4 t/day
  - This assumes a continuous process

Scaling with resistive heating

- Resistive heating is limited by power. Solar arrays are required to provide and convert the heat.
  - Assume constant directly incident illumination.
  - The SOA are the 83 kW solar arrays on the ISS.
- Current production rate is 2 MW.hr/kg.
- With an ISS solar array, this is approximately 1 kg/day.
  - This assumes a continuous process.
  - This is significantly lower than with direct illumination. It is a power limited process.
- RF heating is more effective, but it is unknown how well or how generally it couples to asteroidal material.

The Benefits

- Assuming an optimistic (projected SpaceX costs) $1K/kg of payload mass.
- Assuming a 500 t asteroid volatile-rich, one can produce 200 t of volatiles, and ~90 t of metal.
  - With vacuum pyrolysis one can potentially produce as much as an additional 50 t of oxygen, and 150 t of silica / reduced metals (depending on the feedstock).
- The equivalent launch costs would be at least $2B for the volatiles and $0.9B for the metals.
  - 200 t of LOX/H2 is enabling to get away from NTRs to go to Mars.
- Returning these materials to Earth is not likely to be cost effective.