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night survival heater which also provides some electricity. Details of this system development have been published elsewhere [2], but key to its ability to enable a lunar economy are its various inputs, outputs, and the utility it provides.

The NITE system provides heat via oxidation of metals, and electricity from a fuel cell run off of the oxidation waste products and a liquid oxidizer like hydrogen peroxide. This makes NITE a lunar customer for metal as well as hydrogen peroxide. As will be discussed later, hydrogen peroxide is a compelling option for long-term oxygen storage as well as to balance the production of Hydrogen-Oxygen propellant from lunar ice.

Astrobotic's metal-oxidation based lunar night survival heater, the Nighttime Integrated Thermal and Electricity (NITE) system is this central technology. It runs on a metal-based fuel which can be produced by purchasing unrefined mix-metal slag from Carbothermal Reduction or Molten Regolith Electrolysis (MRE) processes. For oxidizer, NITE can use low concentration hydrogen peroxide developed as a byproduct of lunar ice-based hydrogen-oxygen propellant production, or even by purchasing lunar mined-ice and carbothermal or MRE produced oxygen and processing its own hydrogen peroxide.

The ‘exhaust’ products of heat and power generation by NITE are metal oxides and hydroxides. The metal oxides can be sold back to regolith-based oxygen extractors as a high concentration feed stock, while the hydroxides have numerous applications due to their alkaline nature. Astrobotic has identified opportunities to sell metal hydroxides as a flux for MRE, as well as geopolymerization catalyst for the regolith based construction using geopolymer binder agents.

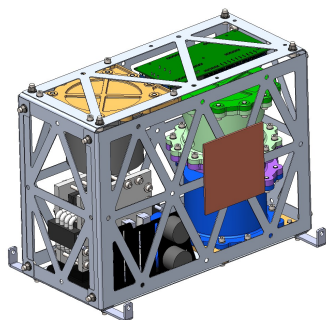


Figure 1 NITE System developed under NACA GCD Tipping Point

**NITE Overview:** Astrobotic has developed its NITE system as a low mass, high energy density lunar

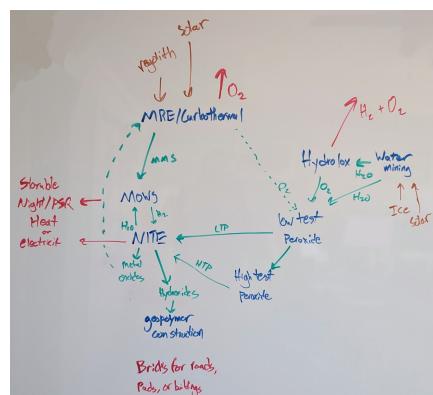


Figure 2 Notional NITE-centered economic cycle

**Purchasing Lunar Derived Metal Fuel:** NITE's metal fuel requirement makes it an ideal customer for the metal slag produced by technologies which extract oxygen from lunar regolith (Carbothermal Reduction

or MRE) such as Sierra Space's CaRD system [3]. While these processes produce a large quantity of valuable un-oxidized metals, then are generally mixed together as a slag of Fe, Al, Ti, Si and others. The refinement and separation of this slag is a nontrivial step towards traditional uses of this metal but becomes unnecessary if the metals can be used in their mixed slag state.

Having a customer who is interested in purchasing slag without further refinement is a significant risk mitigation to Carbothermal Reduction or MRE companies. Their main output of oxygen is only needed intermittently and is challenging to store. By also gaining value from the slag, oxygen extraction is economically derisked. As additional benefit, the oxygen extractors can purchase high purity metal oxides back from NITE to have a higher concentration feedstock for more oxygen extraction. This closes the economic loop for metal and reduces the bulk regolith quantity required for oxygen output.

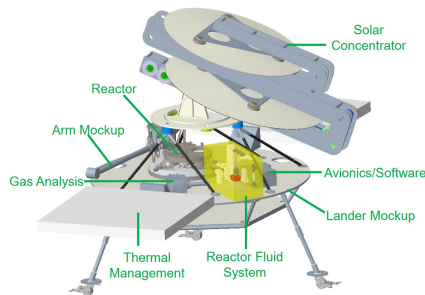


Figure 3 Sierra Space CaRD Carbothermal Reduction System

**Purchasing Hydrogen Peroxide:** While some may argue that hydrogen peroxide is not a useful product on the lunar surface due to decomposition, hands-on experience with long-term storage of hydrogen peroxide in uncontrolled thermal and environmental conditions have informed Astrobotic's view on hydrogen peroxide as a storable resource. Astrobotic sees two viable paths to hydrogen peroxide on the lunar surface.

First, hydrogen peroxide is a useful byproduct of Hydrogen-Oxygen propellant production from lunar ice; the desired Oxidizer to fuel ratio of Hydrogen-Oxygen rocket engines means that direct electrolysis of water will lead to an excess of oxygen. As either a high-pressure gas or a cryogenic liquid, oxygen is challenging to store on the lunar surface. By reacting oxygen with lunar ice-derived water, it can be reacted into hydrogen peroxide, a long term storable liquid.

The second option would be to remove propellant production and directly use oxygen produced from regolith (Carbothermal or MRE) with mined water ice to produce hydrogen peroxide.

As noted, Astrobotic has directly found hydrogen peroxide to be highly storable over multiple earth years with minimal decomposition, so NITE could purchase large quantities for later use without the storage challenges associated with cryogenic hydrogen and oxygen. Beyond its use for NITE and possible propulsion applications, hydrogen peroxide is extremely valuable for human operations as a in-situ produced disinfectant and cleaner.

**The Closed Cycle and Useful Outputs:** As seen in figure 2, the purchase of fuel and oxidizer for the production of heat and power by the NITE system produces a nearly closed economic cycle, with specifically metal and oxygen having the option to be fully closed and used for energy storage. The incomplete closure of this cycle (due to oxygen being sold outside of the loop, and metal hydroxides being used for construction) is actually an economic benefit, as it incentivizes continued mining of resources to replace those leaving the cycle, keeping the system running and ready for expansion as needed.

The core output of the system is the storage of solar energy for later use. However, this cycle has value beyond energy storage as it can accommodate pure oxygen production (for rocket engine or human use) as well as providing feedstock for geopolymer regolith binder construction of landing pads, roads, habitats and more.

The closed loop found in this cycle incorporates a number of different suppliers and consumers, who each add value to the economic cycle at each step. By acting as a central buyer and seller for lunar resources, the NITE system can enable a self-sustaining economic cycle between lunar ISRU producers which can eventually scale to include other buyers and sellers not imagined here, and who themselves can add even more value to this ecosystem, enabled by technology but driven by economic forces.

## References:

- [1] Kevin Barry and Eduardo Pineda Alfaro. ["Changing the ISRU Paradigm from Sustainability to Economic Tool,"](#) AIAA 2021-4030. *ASCEND* 2021. November 2021.
- [2] Slavik and Vazansky, NITE: Surviving the Lunar Night with Metal Oxidation, *ASCE Earth and Space* 2024, April 2024
- [3] Paz, Aaron J. "Carbothermal Reduction Demonstration (CaRD)." *Space Resources Roundtable*. 2023.