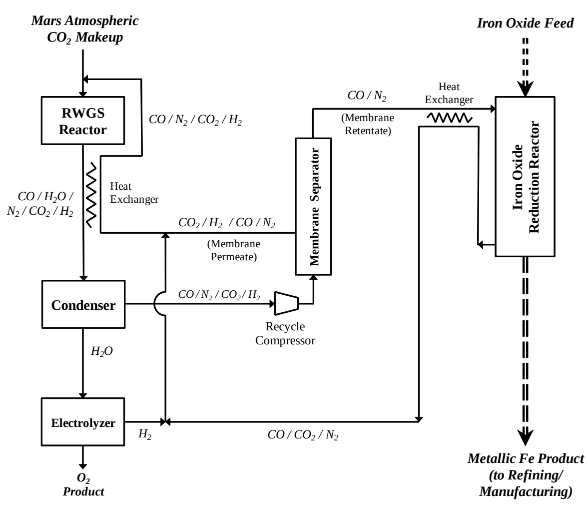
**EXTRATERRESTRIAL METALS PROCESSING.** M. Berggren, R. Zubrin, J. Rasmussen, A. Kennedy, and S. Carrera. Pioneer Astronautics, 11111 W 8th Ave, Unit A, Lakewood, CO 80215; mberggren@pioneerastro.com, zubrin@aol.com, jrasmussen@pioneerastro.com, akennedy@pioneerastro.com, scarrera@pioneerastro.com.

**Introduction:** The Extraterrestrial Metals Processing (EMP) system is an in-situ resource utilization (ISRU) process for iron, steel, and light metals production from Mars resources in support of human space exploration. Iron is produced via carbon monoxide reduction of iron oxide minerals; magnesium is produced via silicothermal or carbothermal reduction of magnesium oxide; silicon is produced via carbothermal reduction; aluminum, titanium, and potentially silicon are produced via magnesiothermal reduction of their oxides. Each feed material is available in undifferentiated soil (and each can be extracted or refined from regolith via physical beneficiation or aqueous processing). However, raw materials rich in iron, magnesium, and silicon are also available in the form of mineral concentrates in selected locations on Mars [1].

Providing a suite of metals for in-situ manufacturing decreases mission dependence on Earth, reduces mission costs and risks, and allows for an expanding extraterrestrial economy. EMP techniques are also applicable to lunar or asteroid resources due to the low consumables requirements for the closed-loop system.

**EMP Iron Production Process:** The production of iron on Mars can be accomplished by reducing hematite ores with carbon monoxide (CO) that is generated from Mars atmospheric $CO_2$ in a process integrated with the reverse water gas shift (RWGS) reaction and electrolysis as illustrated below.




The primary iron oxide reduction reaction is as follows for hematite.

$$Fe_2O_3 + 3\ CO = 2\ Fe + 3\ CO_2$$

A fixed-bed, batch reactor is being used to optimize reduction rates using simulants with a range of $Fe_2O_3$ grades. Carbon monoxide is flowed over the heated bed at various partial pressures in mixtures with $N_2$. Reduction temperatures are between 750-900°C. Use of CO as a reducing agent allows for carbon deposition in the iron product, creating a pathway for production of carbon steels. Strict control of operating parameters such as temperature, pressure, CO concentration and gas flow rate is important to obtain complete reduction of iron oxides along with controlled carbon concentrations in the iron product. A demonstration system to produce 1 kg/day of metallic iron is the target of the current work.

The RWGS reaction produces CO reducing agent from $CO_2$ as follows.

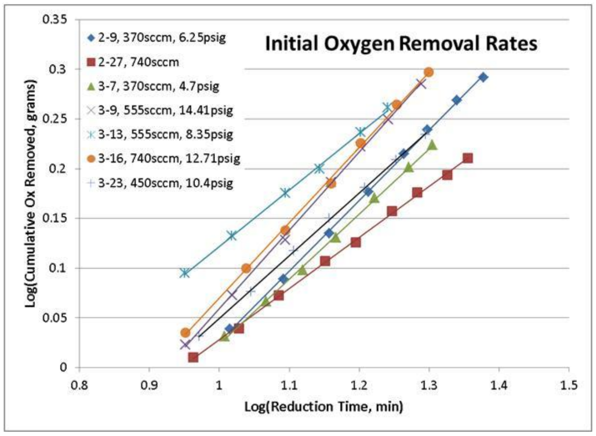
$$CO_2 + H_2 = CO + H_2O$$

Hydrogen (along with co-product oxygen) is generated by electrolysis of water produced by the RWGS reaction. Hydrogen is only present in the RWGS-electrolysis system, while CO, $CO_2$, and $N_2$ are looped between the iron production and RWGS systems. Because the per-pass conversion in the RWGS reactor is relatively low, a recycle system incorporating a gas separation membrane is employed to separate CO from other gases. $N_2$ behaves in a manner similar to CO in the gas separation membrane, allowing for its use and recycle at its intended concentration ranges.

Carbon dioxide produced during reduction of iron oxide is directed to the RWGS for regeneration into CO reducing agent. Because the process operates in a closed loop, Mars atmospheric $CO_2$ acquisition is limited to that required to make up for process losses and for deposition of controlled amounts of carbon in the metallic iron product. Nitrogen can also be acquired from the Mars atmosphere, and its requirement is limited to that required to make up for process losses.

*Iron-Bearing Resources:* Hematite concentrations have been found at Meridiani Planum and other locations [2] and are expected to be at least 70% $Fe_2O_3$ [3]. These potentially rich deposits, often in the form of "blueberries", facilitate the production of metallic iron with minimal upstream beneficiation.

*Product Yields and Grades:* Initial small-scale tests demonstrated EMP feasibility by achieving near 100% reduction of $Fe_2O_3$ powder into iron with small amounts of carbon deposition under the target condition as shown in the figure below.




Results are being applied for scale-up to the 1 kg/day demonstration system. Methods to boost the quality of the iron, including physical beneficiation and molten separations are being evaluated.

**Magnesium Production:** Magnesium was selected as the primary light metal of interest for EMP over aluminum in part due to its availability on Mars in the form of rich sulfate salts (which can be further concentrated by dissolution in water followed by thermal decomposition to magnesium oxide). Magnesium exhibits a high strength-to-weight ratio and is suitable as a structural material in low-oxygen environments. The relatively high vapor pressure of magnesium metal at temperatures near and above its melting temperature of 650°C also enables silicothermal and carbothermal reduction methods as an alternative to the conventional (and more-complicated) molten salt electrolysis technique used for magnesium and aluminum production on Earth.

Vacuum silicothermal reduction of magnesium oxide can be performed as follows.

$$2\,MgO + Si = 2\,Mg + SiO_2$$

This method requires the preparation of a silicon or ferrosilicon reducing agent via carbothermal reduction of silicates (present in Mars or lunar regolith). Silica deposits containing over 90 percent $SiO_2$ have been identified on Mars [4]. The reaction is performed industrially and has been demonstrated by Pioneer Astronautics during previous ISRU work using Mars and lunar simulants [5]. Because the reaction is not thermodynamically favorable, magnesium vapors must be continuously removed to facilitate the on-going reduction of MgO.

Magnesium metal production can be streamlined by direct application of carbothermal reduction as follows.

$$MgO + C = Mg + CO$$

Pioneer is developing a vacuum carbothermal reduction method with targeted operating parameters of about 1250°C and 1 mbar. Quickly separating magnesium vapor from the carbon monoxide product gas is critical to prevent reformation of MgO. This has been demonstrated academically on a limited basis [6][7] but not at all industrially. Pioneer is developing a novel gas-phase technique to rapidly separate magnesium metal vapors from CO. Results will be weighed against power requirements and design complexity to determine the best path forward for magnesium production.

**Other Metals:** With the successful demonstration of magnesium production, a pathway to in-situ production of other metals is opened. Thermitic reduction of silicon, aluminum and titanium oxides using magnesium provides a potential alternative to carbothermal and molten salt electrolysis reductions. Examples are shown in the following reactions.

$$SiO_2 + 2\,Mg = Si + 2\,MgO$$
$$Al_2O_3 + 3\,Mg = 2\,Al + 3\,MgO$$
$$TiO_2 + 2\,Mg = Ti + 2\,MgO$$

Only limited examples of magnesiothermal reduction of another metal oxide have been found in literature [8]. However, thermodynamics indicate the reactions should be nearly complete with pure metal or metal alloys produced. Such methods may be preferable on Mars compared to conventional terrestrial processes.

**Manufacturing with EMP Products:** Multiple EMP manufacturing methods are being evaluated. These include production of iron by sintering, casting, machining and additive manufacturing. Sintering may be conducted on beneficiated, high-grade metallic iron product or on as-is product that may contain various amounts of metal oxides. Crude iron subjected to melting will facilitate liquid-phase refining prior to casting and machining. Additive manufacturing via selective laser sintering, direct metal laser melting and binder jetting will be tested on EMP iron products and equivalent simulants. Manufactured specimens and coupons will be hardness and strength tested. Results will be compared to help determine optimal off-world metal manufacturing solutions.

**References:** [1] Ehlman & Edwards (2014) *AREPS 42*, 291-315. [2] Squyres, S.W. et al. (2004) *Science 306*, 1698-1703. [3] Schneider, A. L. et al. (2007) *LPS*. [4] Squyres, S.W. et al. (2008), *Science 320*. [5] Berggren, M. et al. (2009) *NASA SBIR Contract NNJ06JE51C*. [6] Prentice, Leon H. et al. (2016) *ERMT*, 127-131. [7] Yang, Cheng-bo, et al. (2013) *JMA 1.4*, 323-329. [8] Bolívar, M. Sc R., B. Friedrich (2009) *Proceedings EMC*.

**Acknowledgement:** This work has been conducted with NASA Small Business Innovation Research (SBIR) Phase I and II funding under Contract NNX17CP08C. David Eisenman is the NASA JPL Technical Monitor.