BREAKTHROUGH CONCEPTS FOR MARS EXPLORATION WITH IN-SITU PROPELLANTS. J. J. Szabo[1] and V. M. Hruby[2], [1]Chief Scietist for Hall Thrusters, Busek Co. Inc. (11 Tech Circle, Natick, MA 01760, jszabo@busek.com) [2]President, Busek Co. Inc. (11 Tech Circle, Natick, MA 01760, vhruby@busek.com).

Introduction: The first rigorous proposals for exploring Mars relied upon bringing everything from Earth.[1] The exploration community has since recognized that In Situ Resource Utilization (ISRU) is a necessary component of any feasible, long term architecture.[2] One attractive architecture features the use of non-toxic magnesium (Mg), which is found in the regolith of Mars and the Moon. Mg can serve as a propellant in both chemical (high thrust) and electric (high specific impulse) rockets. Especially attractive oxidizers for a Mg chemical rocket include carbon dioxide (CO_2) and water/steam (H_2O), both of which are readily available in situ at Mars.

For Mars sample return, a Mg-CO_2 rocket could be used to propel the first stage of a Martian Ascent Vehicle (MAV), providing the first practical demonstration of ISRU.[3] In the near-term, the Mg would be carried to Mars in powdered form and combusted with CO_2 that is condensed or compressed from the atmosphere. Once on orbit, an electric rocket fueled by Mg, Xe, iodine or another substance could propel the samples back Earth. In the medium-term, powdered Mg from earth could be combusted with H_2O that is extracted from sub-surface ice. In the far term, the Mg itself would be extracted from the regolith. The architecture greatly enhanced by the use of electrically propelled spacecraft delivery sytems.

Combustion of powdered metals with CO_2 has been studied since at least the mid 1960s,[3,4] and brief static tests of Mg-CO_2 rocket engines have previously been conducted by Wickman Spacecraft & Propulsion Company[5] and by Pioneer Astronautics.[6]

Busek and the Applied Research Lab at Penn State are beginning the development of a Mg-CO_2 Mars sample return rocket. Numerical modeling tools were used to predict the specific impulse at a variety of operating conditions. Then, the concept was successfully demonstrated for over a minute at relevant conditions. Thrust and temperature were measured during the test, enabling a comparison with numerical predictions.[7] In separate work, Busek has demonstrated Mg fueled Hall thrusters.[8]

Properties of Magnesium: Mg is a lightweight metal with an atomic mass of 24.3 AMU. It is a strong substance which may be used structurally, but it is also known for its combustibility. Mg is especially attractive for Martian and Lunar rockets due its abundance in the regolith. Approximately 8.5% of the Martian regolith is MgO while on average 9.2% of the lunar regolith is MgO. One possibility for extracting Mg from the regolith is molten oxide electrolysis. Other possibilities for extracting and refining resources in situ are discussed in the literature.

Near term Martian rockets could combust Mg brought from Earth with the condensed Martian atmosphere, which is over 95% CO_2. The low temperature of the Mars atmosphere favors CO_2 liquefaction. To liquefy CO_2 gas near the surface, the pressure should be increased from around 8 mbar to 10 bar. This can be achieved by different methods, such as mechanical compression, adsorption pumping, and freezing. Mg can also be combusted with H_2O. Water ice has long been believed to exist at the Martian poles and recent photos taken by the Mars Phoenix Lander are direct evidence of its presence near the surface.

Oxidizers are also available on the moon. Ice-rich lunar regolith has been found in the cold-trap areas near the lunar South Pole. Latest analysis of data from Lunar Prospector's neutron spectrometer indicates there may be as much as 300 million tons of water ice contained in the permanently shadowed cold traps near the pole.[9] To extract water ice it may be necessary to construct a regolith reduction reactor, which will work by heating the regolith.

Magneium Chemical Rockets: A rocket produces thrust by expanding a high pressure fluid through a nozzle. Both the fuel and oxidizer are typically stored as liquid, which may be fed by pressure, gravity, or a pump. In metallic bipropellant rockets, the fuel may be stored as a solid powder and delivered in a "fluidized" state with a small amount of background gas. This allows the system to be stopped and restarted.

Specific impulse is often the first consideration when choosing a propellant, and the anticipated vacuum specific impulse of a Mg-CO_2 rocket is comparable to the specific impulse available from hydrazine monopropellant (I_{sp} > 200 s on Mars). Even higher performance, comparable with hydrazine bipropellant and contemporary green alternatives may be generated by combustion with water (I_{sp} >300 s in vacuum)

Other considerations include propellant density, storability, toxicity, and availability of the propellant and oxidizer. Mg-CO_2 combustion is ideally suited for near-term Mars exploration because the oxidizer can be condensed directly from the Martian atmosphere. In this case, an important figure of merit is the effective specific impulse, which is calculated by considering only the fuel. In terms of the oxidizer to fuel ratio,

O/F, the effective specific impulse is equal to $I_{sp}(1+O/F)$.

The Magnesium Architecture: A complete exploration architecture based upon the use of Mg with ISRU is possible. This architecture has the potential to enable radical improvements in terms of higher performance, lower cost, less mass, higher reliability, improved safety, and operational simplicity. Sample return is only the first application.

At Mars, a "hopper" probe[3,4,**Error! Bookmark not defined.**] propelled by a Mg rocket could provide all-access mobility to robots, astronauts, and pioneers. In between hops, the vehicle would refill its tank with liquid CO_2, providing it with great range. A manned hopper would be conceptually similar to the Lunar Landing Research Vehicle (LLRV), developed by NASA Dryden. Other Martian atmospheric mobility applications could include an airplane propelled by a Mg-CO_2 rocket or ramjet. On the surface, a Mg-CO_2 power system could be used to propel a wheeled transport.

The use of Mg is also not Mars specific. Elsewhere (e.g. the moon), Mg can be collected and combusted with water extracted from ice. In space, green Mg-H_2O rockets are competitive with toxic chemical combinations.

Mg is also attractive for high specific impulse electric rockets because is dense, storable, and has a relatively high vapor pressure. Mg is heavy enough to ionize efficiently, but light enough to achieve specific impulse greater than 3000 s at conditions typical of a Hall Effect Thruster.[8] When Mg was tested in a Soviet Hall thruster, efficiencies >50% were measured.[10] One attractive possibility is a multi-mode propulsion system featuring both a Mg rocket and a Mg Hall thruster.

Other related systems include xenon and iodine[11] fueled Hall thrusters, both currently being funded by NASA. The architecture is also enhanced by high power Hall thrusters,[12] and by electrically propelledsmall spacecraft delivery systems being funded by NASA and others.

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