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THE CASE FOR A MARS BASE ISRU REFINERY

Kelly R. McMillen and Thomas R. Meyer

University of Colorado/Boulder Center for Science and Policy, P.O. Box 4883, Boulder, Colorado 80306.

During the early phases of human Mars exploration, in-situ resource utilization (ISRU) will lower costs, expand capabilities, and serve as an enabling technology for establishing permanent colonies. Martian atmospheric resources can be used to provide consumables such as fuel, oxidant, breathable air, and water that are critical for early human missions. Martian atmospheric carbon dioxide and imported hydrogen can be used, for example, as feedstock for the catalytic production of oxygen, methane, methanol, water and other propellants (Zubrin, 1991, 1996, 1997, 1998, Zubrin, Meyer, McMillen 1998, Meyer 1989, 1981). These processes utilize catalytic reactors containing small amounts of iron, nickel and other suitable catalysts, plus gas selective membranes, electrolysis, and other easily implemented gas separation techniques. Waste carbon monoxide from carbon dioxide reduction processes together with hydrogen can be combined to produce other liquid and gaseous fuels and chemical compounds. Excess heat from an exothermic Sabatier reaction can be diverted to minimize heat requirements in endothermic processes such as the reverse water-gas shift reaction. Valuable synergies can be realized by integrating various processes. Oxygen and fuel production processes can be combined so the thermal and material wastes of one process can be utilized by the other thus forming a unique Martian “chemical refinery” that features internal hydrogen recycling and production of a purified carbon monoxide intermediate by-product. Turbines can also be used to recover mechanical energy from high-pressure waste gas and systems can share common hardware and feedstock systems. Chemical feedstock, power, heat and mechanical energy are utilized efficiently and conserved in the design of these robust Martian atmospheric refineries whose technologies may also find applications in industrial waste utilization technology on Earth.

INTRODUCTION

There are several factors which when taken together make a compelling case for establishing a Mars base refinery. These include first and foremost, the ongoing need for large quantities of consumables to support human exploration, the need to minimize the high cost of transporting bulk consumables from Earth, safety considerations that require the maintenance of adequate reservoirs of vital life support compounds, the convenience of valuable readily available feedstocks obtainable from the Martian atmosphere, and options to use innovative materials processing technologies that can be integrated to optimize system performance. In addition, refineries designed to primarily utilize atmospheric gases as feedstock will have a lower environmental impact than surface mining. Finally, this technology is the basis for establishing self-sufficiency on Mars that will make eventual permanent human habitation feasible. Let us elaborate on these points.

MARS BASE ISRU REFINERY:
AN ENABLING TECHNOLOGY FOR HUMAN EXPLORATION

The Mars Base In-Situ Refinery builds on NASA's technological concepts for habitat physico-chemical control features (MSFC 1997) and the original Mars Gas Extractor (Meyer, 1981-Figures 2, 3). It provides the basis for an integrated systems approach to surface exploration by combining consumables production with habitat design. A Mars base can conceivably be constructed piece-by-piece as energy production, reliability and power issues are tested and resolved. Would you rather drive across the Australian Outback with a gas can or build reliability into your chances for survival by constructing a gas station? When asked when he believed we would see the first relay station on Mars, Sir Arthur C. Clarke, replied, "it's a good idea and necessary for extended human missions, I would guess around the year 2030!" This hypothetical schedule requires a long-term plan, implementing a strong synergy between associated processes (oxygen, water, hydrogen and propellant production), high conversion ratios, conservation of mechanical and heat energy and high H_2 leveraging.

CONVENIENCE -
ATMOSPHERIC RESOURCES ARE BOTH USEFUL AND UBIQUITOUS

As a major component in the Martian atmosphere (95.3%), carbon dioxide is a candidate feedstock for the manufacture of oxygen, propellants, and a whole range of Fischer-Tropsch products (Frankie, this volume). Compounds manufactured from CO_2 and hydrogen can be stored easily in ambient Mars conditions (+ 15°C to - 100°C).

Figure 1 Materials Freezing and Boiling Points. (Adapted from B. C. Clark, 1991).

A Pulse Tube Refrigeration system (PTR) that contains no movable parts and in which heat transfer between the gas and the tube wall follows linearized conservation equations, could suffice for liquid storage of hydrogen, methane, and oxygen on the surface of Mars. Oxygen can be stored in either a gaseous (GOX) or liquid (LOX) form under these conditions. Compression of carbon dioxide for use as a cryogen may also be feasible on Mars' surface.

SAFETY - A MARS BASE REFINERY INCREASES SAFETY AND ROBUSTNESS

A key function of a Mars Base Refinery will be to accumulate and maintain reservoirs of consumables. The amount of each compound held in reserve will depend on safety and expected system-loading requirements. These represent an important safety reserve that can be used during refinery maintenance downtime and in the event of emergencies.

NEED: SCIENTIFIC EXPLORATION REQUIRES CONSUMABLES

The primary purpose for developing a Mars Base refinery is to supply consumables such as air, water, and fuel for scientific exploration. Mars holds a vast trove of scientific knowledge that will help us better understand and protect our own planet, understand the origin and evolution of our solar system, and gain important insights into origin of life. Mars is also a laboratory for habitability research where we can appraise the feasibility of modifying the Martian climate and adapting terrestrial species that might facilitate eventual human habitation of Mars. Such studies will merit the establishment of manned bases and laboratories on Mars that are comparable to those in Antarctica and whose research operations could easily span many decades. NASA's life support systems will assist in attaining basic self-sufficiency on Mars.

Table 1

ESTIMATE OF CONSUMABLES USE BY MARS BASE ELEMENTS

ISRU AS AN ENABLING TECHNOLOGY FOR EXPLORATION: LOWERS COSTS & MASS

ISRU is an enabling technology for exploration because it drastically lowers the transportation costs of importing consumables, particularly rocket propellant needed for ascent vehicles for return to Earth. Since it takes on the order of 100 tons of liquid oxygen and propellant to return a crew of five persons from Mars surface back to Earth, and since the transportation cost to deliver material to the surface of Mars is in the range of $20-$50,000 per kilogram, if this fuel can be produced from local resources on Mars, then a an enormous savings in transportation costs can be achieved. In fact, this savings could be the critical factor that determines whether a human exploration program is feasible at all.

In the early stages of exploration, the logistical difficulty of obtaining water on Mars suggests a strategy where the hydrogen component of the propellant would be imported from Earth while the remainder of the constituents are obtained from Mars resources as proposed in the Mars Direct scenario (Zubrin and Baker 1984, 1991).

As an illustration consider a rocket that uses oxygen and methanol propellant. From the combustion equation we see that

$CH_3OH + 1.5\ O_2$ ® $CO_2 + 2\ H_2O$ DH = -675.72 kJ/mol of CH_3OH

If we add the mass in atomic weight units of each element, we have 12 units of carbon, 40 units of oxygen, and 4 units of hydrogen for a total of 56 units for each molecule of methanol burned. Of this 52 units represent material that could be obtained by processing Martian atmospheric carbon dioxide while the remaining 4 units consist of hydrogen that would initially be imported from Earth. Since the hydrogen represents only about 7% of the entire mass of the fuel, this translates into very significant savings over shipping the entire mass of fuel at a cost of several billion dollars for each crew of 5 persons to be returned home from Mars. As another example, if ethylene, a more powerful propellant could be synthesized on Mars, the amount of hydrogen required drops to only 3.2%.

$C_2H_4 + 3\ O_2$ ® $2\ CO_2 + 2\ H_2O$ DH = -1322.49 kJ/mol C_2H_4

Thus a Mars Base Refinery that is able to produce water, oxygen and ethylene would be a tremendous asset for human exploration. Table 2 summarizes the mass leverage of in-situ propellant for Earth-derived hydrogen.

Table 2

IN-SITU PROPELLANT MASS LEVERAGE[a]
FOR EARTH-DERIVED HYDROGEN RELATIVE TO TERRESTRIAL H_2/O_2 FUEL

REVERSE WATER-GAS SHIFT (RWGS) AS AN EXAMPLE OF AN INTEGRATED SYSTEM

The reverse water-gas shift (RWGS) reaction coupled with water electrolysis and ethylene production can be configured to produce oxygen from Mars atmospheric carbon dioxide using a continuous flow process that operates at moderate temperatures and pressures and is easily scalable (Zubrin, Meyer, McMillen 1997) (figure 4). An adsorption-based separator is recommended for separating out the component gases and filtering the aerosols from the Mars atmosphere. The reason for this is that at the low temperatures of the Martian night, CO2, loading can approach theoretical limits for certain adsorbents. Operating on the change in temperature from day to night, this diurnal cycle provides an effective optimization for use of adsorbent mass (Flynn, McKay, Sridhar, 1996). Additionally, under the low-pressure conditions of Mars, adsorption pumps are often able to produce pressure ratios much larger than single-stage mechanical compressors. They use fewer moving parts and are more easily scaled to small dimensions than are mechanical methods.

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Figure 2 The Gas Extractor (Meyer, 1981).

The feedstock for this process is ubiquitous carbon dioxide and an initial charge of imported hydrogen. Since hydrogen is not consumed and can be recycled, this makes possible the design of a continuous flow oxygen production system where the only other feedstock requirement is for additional hydrogen (or water) to compensate for system losses.

Figure 3 Carter Emmart's Concept of the Gas Extractor (Meyer, 1981).

Figure 4 RWGS Integrated System for Water and Ethylene Production.

Table 3

MATERIALS THAT CAN BE MADE USING MARS AIR

CONCLUSION

On Mars your footprints are forever. Atmospheric refineries will have less impact on the Martian environment than surface or subsurface mining. Optimal use of Martian natural resources is assumed during the atmospheric refining process in which carbon dioxide is filtered from the air. All carbon that is taken out of the atmosphere is returned upon combustion or upon reoxidation of the carbon monoxide. The CO is recycled inside the catalytic reactor to produce fuel or propellant. So our net usage is zero. Nothing is removed from the environment.

An integrated ISRU Refinery offers redundancy, energy savings, conservation of feedstock, and recycling of waste products: heat, materials, and mechanical energy. Examples: energy savings - RWGS can use waste heat from SE, conservation of feedstock - waste CO from RWGS is feedstock for In-Situ Propellant Production (ISPP). Ways to improve the efficiency of various processes by integrating them into a Mars Base Refinery include using waste heat from one process to supply another efficiency is improved by using the waste product form one process as feedstock in another (figure 5). Likewise, recovery of mechanical energy from the high-pressure exhaust of one process enables optimization of mechanical efficiency that improves the efficiency of the entire refinery system.

Future - ISRU is the basis for self-sufficiency, and the foundation for future expansion and eventual colonies. On Earth, the atmospheric refinery is an experimental testbed for design of energy efficient integrated systems with industrial applications and in extreme environmental outposts such as the Antarctic, Arctic or desert communities.

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