IN-SITU RESOURCE UTILIZATION TECHNOLOGIES FOR MARS LIFE SUPPORT SYSTEMS

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ABSTRACT

The atmosphere of Mars has many of the ingredients that can be used to support human exploration missions. It can be “mined” and processed to produce oxygen, buffer gas, and water, resulting in significant savings on mission costs. The use of local materials, called ISRU (for in-situ resource utilization), is clearly an essential strategy for a long-term human presence on Mars from the standpoints of self-sufficiency, safety, and cost.

Currently a substantial effort is underway by NASA to develop technologies and designs of chemical plants to make propellants from the Martian atmosphere. Consumables for life support, such as oxygen and water, will probably benefit greatly from this ISRU technology development for propellant production. However, the buffer gas needed to dilute oxygen for breathing is not a product of a propellant production plant. The buffer gas needs on each human Mars mission will probably be in the order of metric tons, primarily due to losses during airlock activity. Buffer gas can be separated, compressed, and purified from the Mars atmosphere. This paper discusses the buffer gas needs for a human mission to Mars and consider architectures for the generation of buffer gas including an option that integrates it to the propellant production plant.

INTRODUCTION

Practically all the resources needed to support a human mission are available in some form on the surface of Mars. Several mission analyses (French, 1989; Zubrin, 1991a; Sridhar, 1995) have shown that reliance on Martian resources for life support consumables would significantly reduce the cost of a human mission to Mars as well as reduce the risks. Air revitalization in the habitat is an essential part of all human missions, and the total amount of consumables that needs to be generated or regenerated for human life support is fairly well defined. The quantities of the consumables will scale with crew size and mission duration. In the early phases of human exploration, it is likely that heavy reliance will be placed on closure of the consumable loops and the tendency will be to carry all the needed consumables from Earth. However, an assessment of the make-up quantities needed indicates that the loss of gases from the airlock during extravehicular activities (EVAs) alone is in the order of metric tons. Generation of these gases from Mars resources would be a viable option. It is to be noted that during field operations on Mars, where the physical efforts of the crew are high and the regeneration loops may not be as efficient as on the base due to mass and power considerations, the need for make-up gases may be even higher. The availability of buffer gas that can be produced on Mars may permit the scrubbing of space suits with high-pressure gas to get rid of the fine dust particles. The availability of Mars-generated consumables could significantly extend the duration and range of crew operations and greatly enhance the science returns from the early missions. It is also important to realize that assessing and developing the technologies necessary for generating life support consumables would lay the foundation for determining if Mars has the resource potential for a long-term human settlement (McKay *et al.*, 1991).

The concept of in-situ resource utilization, or ISRU, to reduce the cost and mass of Mars missions is not new. In 1978, a study by Jet Propulsion Laboratory (JPL) (Ash *et al.*, 1978) quantified the benefits of producing methane and oxygen from Mars resources for a robotic sample return mission. All the major studies conducted by NASA in the recent past have identified the need for utilizing space resources as an essential technology for future space exploration. The Human Exploration and Development of Space (HEDS) Strategic Plan identifies ISRU as an enabling technology that needs to be developed for human exploration and states, "*… the long term emphasis will be on the use of resources and environments of planetary bodies for the benefit of humankind and to sustain a human presence beyond Earth*" (NASA Headquarters, 1998).

The atmosphere of Mars has several gases of interest to life support and propellant production. Its composition is predominantly carbon dioxide (95.3 volume percent) with significant amounts of nitrogen (2.7 volume percent) and argon (1.6 percent). The technology development program for in-situ propellant production (ISPP) on Mars is well underway. The focus of that program is to produce oxygen and hydrocarbon fuels (methane, ethanol, etc.) from Earth-carried hydrogen and Mars atmospheric carbon dioxide. While the oxygen and water needs for life support could potentially be met with the ISPP technology program, the need for buffer gas will not. In this paper we will walk through scenarios where the life support program could develop its own buffer gas generation plant or, better still, use a modified version of the ISPP plant that also generates buffer gas. Both of these scenarios would be realized if research into buffer gas generation on Mars occurs soon and the technology roadmap for life support ISRU is synchronized with the ISPP technology development roadmap.

In the next section, we show why buffer gas (a mixture of nitrogen and argon) ranks so highly as a made-on-Mars consumable. Next, we will discuss how its manufacture might be integrated in a chemical plant that produces methane and oxygen for propellant and water as a by-product. Adsorption-based separation and compression, a candidate technology for the production of buffer gas from Mars atmosphere, has been described in detail elsewhere (Finn *et al.*, 1996a, and 1996b).

BACKGROUND AND SIGNIFICANCE

In this section, we make the case that the mass penalties of a life support system for Mars can be reduced dramatically using ISRU technology. All life support systems are open to some extent; none is completely closed, despite the use of the best recycling techniques imaginable. On missions of sufficiently short duration, such as *Apollo* or Shuttle, it is reasonable to carry all consumables with the crew. On longer-duration missions, economics begins to favor closure of the life support system since it results in reduced launch mass and storage costs of consumables. If the longer-duration mission is to low-Earth orbit, such as to *Mir* or to the International Space Station, resupply can reduce the burden of storing and recycling consumables. However, for missions that are long-duration and have very distant destinations, such as a mission to Mars, resupply is not considered practical.

A preliminary Mars Reference Mission (MRM) has recently been proposed (Hoffman and Kaplan, 1997) that represents a reasonable scenario, supported with good arguments, for a human exploration mission to Mars. While the document does not represent a mission architecture decision by NASA, it is an excellent foundation upon which to base a study of the value of in-situ generated consumables for a life support system on a Mars mission. They have selected a "fast-transit" trajectory, to minimize crew exposure to interplanetary radiation and zero gravity, to maximize productivity on the Martian surface, and to allow flexibility in an ongoing Mars exploration program. The actual transit and stay times vary slightly with launch opportunities in different years. However, a 180-day outbound, 600-day stay, and 180-day return are numbers commonly used for planning purposes. These numbers allow us to estimate the total quantities of consumables required for a mission.

The ubiquitous resource on Mars for materials utilization is its atmosphere. The atmosphere of Mars is composed of, on a molar basis, 95.3% CO_2, 2.7% N_2, 1.6% Ar, 0.13% O_2, 0.07% CO, and other trace gases. These components of the atmosphere can be potentially compressed from the nominally low ambient pressures, separated, reacted with hydrogen (extracted from Mars water, or carried from Earth), and processed in a variety of ways to produce rocket propellant and life support consumables. Buffer gas production, while discussed in the MRM as a life support need that may be provided by ISRU technology, is neither a need nor a by-product of the ISRU propulsion plant.

Significance of Buffer Gas Cache on Mars

Buffer gas will be lost via leakage throughout the duration of the mission and via airlock activity involving the habitat and pressurized rover during the Mars surface stay. Although the structures of the Mars transit vehicle and surface habitat have not been determined (an inflatable design has been proposed), these environments will have seams and seals through which leaks will occur. The U.S. Laboratory of the International Space Station (Boeing, 1997a) will leak at a rate of approximately 0.1 kg/day, and the leak rates from the transit vehicles and habitats for the MRM are likely to be similar. Given such leak rates, roughly 100 kg of buffer gas will be lost over an entire MRM.

Airlock activity can represent a significant loss of buffer gas if activity cycles are frequent. The crew airlock for Space Station is used to don-doff suits and to perform suit maintenance, therefore they must be pressurized and have a significant volume — in the order of 10 m^3 (Boeing, 1998). Air is pumped out of the airlock before it is opened to space vacuum, but residual gases remain. For Space Station, about 10% of the air, almost 1 kg of buffer gas, in the airlock is lost during each transition (Wieland, 1994). The Mars airlock design may be different from that used on Space Station. It may have a higher loss per cycle because of the probable need to flush with buffer gas to prevent Mars atmospheric gases from entering the habitat and causing back-contamination. Hatch-back suits may be used that reduce the frequency of airlock pressurization cycles, but this approach may result in large gas losses when suits require maintenance — possibly a high-frequency task, given the dusty Mars environment and heavy use. There may also be additional airlocks used on Mars for EVAs from pressurized rovers and for equipment. About 1200 kg of buffer gas will be lost due to airlock activity per mission.

The total for leakage and airlock activity is approximately 1.3 metric tons of buffer gas per mission. The MRM document cites a total of 3.9 metric tons required for three missions, so our estimation appears to be quite consistent with that of the MRM document. It is to be noted that several other sources of leakage, such as airlock activity from a pressurized rover, leakage rates in space suits, and gases lost in removing fine dust from suits have not been taken into account in the above estimation. A safety margin is also useful, to accommodate unexpected events. A safety factor of two brings the total to 2.6 metric tons per three-year mission. By comparison, the resupply rate of nitrogen to the International Space Station after assembly is approximately 0.8 metric tons per year (Boeing, 1997b), or 2.4 metric tons for three years (MRM total duration).

Given the large make-up mass of buffer gas, the potential for significant mass savings by generating it on-site and the enhanced safety factor associated with having a known cache in place prior to human exploration clearly make buffer gas production a worthwhile consideration for life support.

ARCHITECTURES FOR BUFFER GAS GENERATION

An ISRU chemical process plant must be highly optimized for the products it manufactures, due to the high costs of launch mass and power generation and the need for safe and extremely reliable operation. In this section we consider three ISRU plants: one aimed primarily at producing propellant only, one for life support only, and a third that produces both propellant and life support consumables.

Propellant Production Only

As per the MRM document, an ISRU propellant production plant needs to produce 20 metric tons of O_2 and 6 metric tons of CH_4 for each ascent vehicle. This is an optimal mixture for a CH_4–O_2 rocket. The generation might be accomplished in a chemical production plant as shownin the schematic in Figure 1.

The basic plant consists of three main unit operations: (1) a compressor that brings the low-pressure (6 mbar) Mars atmosphere up to the required pressure (typically 1 bar), (2) a CO_2 reduction reactor that reacts CO_2 with H_2 transported from Earth or recycled on Mars, and (3) a water electrolyzer that produces O_2. The technologies used in the propellant production plant would be chosen based on mass, power, and reliability considerations. Some options currently being considered for the compressor include mechanical compression, cold-trapping of CO_2, and temperature-swing adsorption. Sabatier, reverse water-gas shift, solid oxide electrolysis, or combinations of these. are CO_2 reduction reactors under consideration. Each choice has an effect on the amount of Mars atmosphere processed, but the main objective is production of CH_4 and O_2 in the optimal ratio for rocket engine performance.

Fig. 1. Schematic of ISRU plant for production of propellants.

It is important to note here that buffer gas, a nitrogen-argon mixture, does not appear as a process stream. Separation and purification of this mixture adds energy costs, additional complexity in CO_2 acquisition, and equipment mass. At best, a gas mixture somewhat enriched in these components will be discarded as a waste gas. If mechanical compression or cold trapping is used for compression, it is unlikely that even the low-purity buffer gas would be available.

Life Support Consumables Only

One possible plant schematic that considers life support needs only is shown in Figure 2. The product driver in this plant is 2.6 metric tons of buffer gas. Nitrogen and argon are present in the Mars atmosphere at 3.2 weight percent; approximately 30 metric tons of CO_2 are processed (filtered of dust and compressed) during the buffer gas extraction process. This CO_2 is more than sufficient for production of suitable caches of oxygen and water. Carbon dioxide is also available for use in a small greenhouse and a variety of other applications.

Technologies selected for the unit operations would likely be quite different from those chosen for propellant production alone. For example, an adsorption separation device can produce a high quality buffer gas stream while also providing a suitably compressed feedstock for the CO_2 reduction unit. If CH_4 is produced, it is not of particular value for life support, hence, it is pyrolyzed to recover hydrogen. If CO_2 electrolysis is used as the reduction technology, no CH_4 is produced and water can be brought directly from Earth, eliminating the need for water electrolysis and CH_4 decomposition equipment, plus the power to operate them.

Fig. 2. Schematic of ISRU plant for production of life support consumables.

Integrated Propellant Plus Life Support Consumables Production

A plant design that combines the objectives of the propellant production and life support consumables production is shown in Figure 3.

Fig. 3. Schematic of ISRU plant producing both propellant and life support consumables.

Oxygen production for propellants use (20 metric tons) probably drives the amount of Mars atmosphere required. However, the buffer gas requirement can drive both the choice of CO_2 reduction and compression/separation technology. A carefully designed adsorption separation unit can produce both high quality buffer gas and compressed CO_2, albeit at a higher power consumption than an adsorber designed only to perform compression.

As an example of the effects of choice of CO_2 reduction technology, consider that a Sabatier/water electrolysis system reactor produces about 75 kg of O_2 for each 100 kg of CO_2 feedstock according to the following reactions which occur with nearly 100% yield:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \text{ (Sabatier)} \tag{1}$$

$$2H_2O \rightarrow 2H_2 + O_2 \text{ (water electrolysis)} \tag{2}$$

According to the stoichiometry of the Martian atmosphere, 100 kg of atmospheric CO_2 is accompanied by 3.2 kg of buffer gas. This gives an oxygen:buffer gas production ratio of about 75:3.2, so 0.9 metric tons of buffer gas could potentially be produced along with 20 metric tons of O_2 using this technology, assuming perfect efficiencies. This is well below the 2.6 metric ton stock we estimate would be needed for each mission to Mars.

As a counter example, CO_2 electrolysis technology produces 30 kg O_2 for each 100 kg CO_2 feedstock (Sridhar, 1997) according to the reaction

$$CO_2 \rightarrow CO + 1/2O_2 \tag{3}$$

which would operate at roughly 80% efficiency for this application. The oxygen:buffer gas production ratio is 15:3.2, so in principle 2.15 metric tons buffer gas might be produced as a result of choosing this CO_2 reduction technology, easily satisfying the need for a buffer gas cache.

This order-of-magnitude analysis illustrates the impacts that technology selection can have on production rates of the various products that might be obtained from the Martian atmosphere. A number of other factors must of course be considered (especially power consumption) for a more accurate analysis.

CONCLUSIONS

A life support system for Mars will carry a consumables burden, despite the use of state-of-the-art technology to approach closure of air and water loops. One of the chief consumables will be buffer gas, lost primarily through airlock cycles. Extravehicular activity will be heavy on the surface, leading to airlock losses of approximately 1.3 metric tons of buffer gas per mission (2.6 if a safety factor of two is used) -- a significant mass penalty that may be dramatically reduced through the use of ISRU technology to extract buffer gas from the Martian atmosphere. A combined ISPP and life support ISRU plant has the potential to offer mass and power savings.

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