In Situ Utilization of Indigenous Resources

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Abstract

In situ resource utilization (ISRU) on the Moon or Mars is an approach for converting indigenous resources into various products (primarily propellants and life support consumables) that are needed for a space mission. By utilizing indigenous resources, the amount of materiel that must be brought from Earth may be reduced, thus reducing the *Initial Mass in Low Earth Orbit* (IMLEO.) IMLEO is typically used as a measure of the mission scope and cost.

Lunar ISRU suffers from the need for high-temperature processing or a lack of abundant accessible feedstocks, depending on the process. Several approaches are under study but the practicality of these processes is doubtful. In addition, NASA lunar mission planning appears to include approaches and requirements that may reduce or even obviate the potential for ISRU to provide mission benefits.

By contrast, Mars ISRU processes are simple to implement and they utilize abundant resources. The potential mission impact is significant. The key to practical Mars ISRU is acquiring water as a feedstock from near-surface deposits that have been discovered from orbit with a neutron spectrometer.

Unfortunately, several years ago, NASA stopped funding Mars ISRU (which is practical) and is presently funding lunar ISRU (which appears to be impractical). Furthermore, NASA's Mars Program does not seem to have any intention of exploiting these water resources for leveraging Mars surface missions.

1. Value of ISRU

In situ resource utilization (ISRU) on the Moon or Mars is an approach for converting indigenous resources into various products that are needed for a space mission. By utilizing indigenous resources, the amount of materiel that must be brought from Earth may be reduced, thus reducing the *Initial Mass in Low Earth Orbit* (IMLEO.) IMLEO is typically used as a measure of the mission scope and cost. Mars mission planners deal extensively with IMLEO, and the problems involved in launching that materiel and sending it out of LEO on its way toward Mars.

ISRU has the greatest value when the following ratio is large:

R = [mass of products supplied by ISRU to mission] / [mass of the ISRU system brought from Earth]

Thus in order for ISRU to have net value, it is essential that the mass of the ISRU system (i.e. the sum of the masses of the ISRU plant, the power plant to drive it, and any feedstocks brought from Earth) must be less than the mass of products produced and used by the mission. If $R >> 1$, then in comparing the IMLEO for two similar missions, one using ISRU, and the other not using ISRU, the IMLEO using ISRU will be lower. This comparison of IMLEO with and without ISRU will provide one measure of the "value" of ISRU. However, from a broader point of view, one should compare total investments (rather than IMLEO) with and without the use of ISRU. In this regard, the investment in ISRU includes the costs of (a) prospecting to locate and validate accessibility of indigenous resources, (b) developing and demonstrating capabilities to extract indigenous resources, (c) developing capabilities for processing indigenous resources to convert them to needed products, (d) additional operational costs in running or servicing ISRU systems in space, and (e) any ancillary requirements specifically dictated by use of ISRU (e.g. possibly a nuclear power system). The potential cost saving that might be realized by using ISRU is essentially equivalent to the investment that is eliminated by reducing IMLEO for as many launches as the ISRU system serves. If this potential cost saving is greater than the investment required to develop and implement ISRU, then ISRU has net value for a mission or a set of related missions. If one only compares ISRU system mass with ISRU product mass, one may in some cases conclude (incorrectly) that ISRU is beneficial, when in actuality, ISRU adds to the overall mission cost. Typically, NASA plans human missions without the use of ISRU, and then considers tacking on ISRU rather late in the campaign as an embellishment. This limits the benefits of ISRU because all vehicles are sized without taking into consideration the benefits that ISRU could yield.

In the short run (next ~ 40 years) the main products that might be supplied to human missions by ISRU are:

- Propellants for: 1) ascent of return vehicles, and 2) intra-surface transportation, thus reducing the mass of ascent propellants that otherwise would need to be brought from Earth.

- Life support consumables (water and oxygen). It is possible that while on the surface, the usual life support cyclic system could be eliminated or downsized by using ISRU as an alternative to provide these consumables.

In addition, in principle, regolith can be piled up on top of a habitat for radiation shielding. However, it remains to be seen whether NASA designs for surface habitats allow for use of regolith as shielding from radiation. Existing designs for lunar and Mars habitats do not appear to be compatible with regolith radiation shielding.

In the longer run, it is possible that a wider range of products could be produced as the industrial and electronic revolution is transferred from Earth to extraterrestrial bodies. Unfortunately, there does not seem to be a clear path leading from where we are now to such an ultimate utopia.

Although this book is primarily focused on Mars, it is worthwhile to also examine NASA plans for lunar ISRU because NASA seems to be intent on concentrating its resources and efforts on lunar ISRU for the next couple of decades, and lunar ISRU is viewed by many as a stepping-stone to Mars ISRU.

2. Potential Products

The NASA Human Exploration Initiative views lunar exploration as a stepping-stone to Mars. One of the important stepping-stones is demonstration of ISRU technology. The term "ISRU" occurs 106 times in the 2005-6 Exploration Systems Architecture Study (ESAS) Report, and the choice phrase “living off the land” occurs several times.

Most discussions of lunar ISRU seem to assume that resources are readily available, and they proceed to emphasize processing, while minimizing logistics (prospecting, excavating regolith, regolith transport, deposition into and removal of regolith from reactor, dumping waste regolith, etc.) However, the quantity and composition of end products provides the basis for considering the use of ISRU as well as for setting the requirements for ISRU systems. Therefore, we begin here with the potential end products.

2.1 Lunar Ascent Propellants

In the initial NASA ESAS architecture of 2005-6, the propulsion system for ascent from the Moon was based on $CH_4 + O_2$ propellants in order that ISRU-generated oxygen from the Moon could be utilized in place of oxygen brought from Earth. Although methane would need to be brought from Earth, use of the $CH_4 + O_2$ propulsion system provided an implicit connection to Mars ISRU by using oxygen as the oxidizer for ascent. Later, when the realities of cost and schedule to develop the CH_4 + O_2 propulsion system became clearer, this ascent propulsion system was dropped in favor of space storable propellants that are incompatible with lunar ISRU. Yet, NASA continued to claim that ISRU was a major part of the lunar exploration program!

In the original 2005-6 architecture, the plan was to have two ascents per year from a polar outpost, each requiring about 4 metric tons (mT) of oxygen, for an annual need of roughly 8 mT. However, in a NASA release in February 2007 [1] NASA persisted in specifying space storable propellants for ascent, and these propellants are incompatible with ISRU.

Since the "gear ratio" (required mass in LEO/mass delivered to surface) for lunar polar outposts is about 4:1, the potential mass saving in LEO from use of ISRU is ~ 16 mT per launch. However, because the launch vehicles were designed without using lunar ISRU, their designs will remain unaffected by later inclusion of lunar ISRU in the missions. Nevertheless, they would not need to carry 4 mT of oxygen if ISRU were employed. Hence they would be able to deliver an extra infrastructure payload (~4 mT) to the outpost with each launch (but rather late in the campaign - probably beginning in the late 2020s). (Even this minor benefit disappears if NASA persists in its present plan to use space storable propellants (NTO/MMH) for ascent, thus eliminating oxygen as an ascent propellant.) The "value" of the ~4 mT increase in payload delivery per launch using lunar ISRU can be estimated by noting that over a period of years, with continual infrastructure deliveries to the outpost, a cargo delivery launch might be eliminated once every several years with small incremental increases in mass delivered by each launch.

However, if the design policy "abort to orbit" remains a requirement for descent, then there is no possibility of providing ascent propellants using ISRU since the incoming Lunar Surface Access Module (LSAM) would have to possess ascent propellants as a safety measure.

2.2 Mars Ascent Propellants

A vital ISRU product of relevance to Mars missions is oxygen for use as a propellant in ascent from Mars. This oxygen would be stored as a cryogenic liquid in the Mars Ascent Vehicle (MAV) on the Mars surface. The amount of oxygen required will depend on several factors: (1) the mass of the capsule to hold the crew during ascent and rendezvous, (2) the number of crew-members, (3) the orbit in which rendezvous takes place, and (4) the fuel propellant used in conjunction with the oxygen. In a typical rocket using oxygen as the oxidizer (e.g. methane-oxygen rocket) the oxygen accounts for 75-80% of total propellant mass depending on the actual mixture ratio used. Thus if the methane (or hydrogen to produce methane from the CO_2 in the Mars atmosphere) is brought from Earth, and ISRU produces only oxygen from Mars feedstocks, ISRU would still provide 75-80% of ascent propellant needs. Some forms of Mars ISRU produce not only oxygen, but methane as well. In that case, 100% of ascent propellant needs would be supplied by ISRU.

2.3 Life Support Consumables

Mars ISRU can also be used to produce life support consumables. The requirement for the surface phase of a human mission to Mars with a crew of six was given in Table 4.2 of *HMMDR*. The requirement is for about 100 mT of water and about 4 mT of oxygen. ISRU would supply these commodities. However, the mass benefit from using ISRU to supply these commodities depends on assumptions made regarding the efficiency and mass of competing recycling systems for these commodities. It is likely that the systems for air and water recycling in an Environmental Control and Life Support System (ECLSS) would have considerably lower mass than the 104 mT of commodities, but the longevity and reliability of such systems remains open to question.

HMMDR estimated the reduction in IMLEO that would result from use of ISRU to produce methane and oxygen on the Martian surface from indigenous resources. The total propellant requirements for three operations were included (orbit insertion, ascent, and orbit departure). It was found that the benefit from ISRU was much greater if an elliptical orbit is employed for staging. The reason for this is that entry into an elliptical orbit is easier (i.e. requires less propellant) than entry into (and exit from) a circular orbit, but ascent to a circular orbit is much easier than ascent to an elliptical orbit. However the higher propellant requirement for ascent to an elliptical orbit can be furnished by ISRU. Based on a particular mission concept, the reduction in IMLEO from use of ISRU was estimated by *HMMDR* to be about 130 metric tons (mT) using a circular orbit for staging, and about 370 mT using an elliptical orbit.

The mass saving due to ISRU propellant production is even greater if a mission architecture is used in which the Mars Ascent Vehicle (MAV) does not rendezvous with an Earth Return Vehicle (ERV) in Mars orbit, but instead, the MAV goes directly from the Mars surface all the way back to Earth. The Mars Direct [2] and Mars Society [3] missions used this approach, and the MIT study [4] found significant benefits to this architecture. However it appears unlikely that NASA will consider this approach.

Oxygen requirements depend on crew activity but an average value is about 1 kg per crew-member (CM) per day. Water requirements have been estimated by JSC to be about 27 kg/CM-day. (See Table 4.1 of *HMMDR*).

To support a crew of 6 for one year, we require 6 × 1 × 365 = 2,190 kg ~ 2.2 mT of O_2, and 6 × 27 × 365 ~ 60 mT of water.

It is likely that an ECLSS would be used to recycle these resources, thus greatly reducing consumable mass requirements. Therefore, the benefit of ISRU is not replacement of resources, but rather replacement of the mass of the ECLSS. JSC has estimated the mass of ECLSS systems. Using ISS experience as a basis, JSC estimated the mass and power requirements of ECLSS systems for a crew of six on Mars for 600 days as shown in the following table:

System	Physical plant mass (kg)	Backup cache mass (kg)	Total mass (kg)
Oxygen ECLSS	765	570	1,335
Water ECLSS	6,750	4050	10,800

For a typical Mars mission design, the stay on the surface would be about 1.5 years, so the total water/oxygen requirement would be about 93 mT for a crew of six, and the estimated mass of the ECLSS to supply these resources would be 18 mT. However, this estimate of the ECLSS mass is based on very sparse data and may represent an optimistic evaluation. Furthermore, if an ISRU system were used to supply water and oxygen, an ECLSS would still be required to maintain environmental requirements even if recycling is not used. However, such an ECLSS would be much less complex than one that recycles.

2.4 Propellants Delivered to LEO from the Moon

For a typical Mars-bound vehicle in LEO prior to trans-Mars injection, about 60% of the total mass in LEO consists of H_2 + O_2 propellants for trans-Mars injection. If Mars-bound vehicles could be fueled in LEO with H_2 and O_2 delivered from the Moon, then only the remaining 40% of the total vehicle wet mass would need to be delivered from Earth to LEO. The other 60% would be provided from lunar resources. For example, a Mars-bound vehicle that weighs say, 250 mT in LEO, would include about 150 mT of propellants for trans-Mars injection. If fueled by hydrogen and oxygen from the Moon, the mass that would have to be lifted from Earth to LEO would only be about 100 mT instead of 250 mT. This would have a huge beneficial impact on the feasibility of launching large Mars-bound vehicles.

In this regard, the question that we must deal with is: how feasible is it to transfer water (and then by electrolysis, produce $H_2 + O_2$) from the Moon to LEO? If this process is efficient, the scheme of supplying propellants to LEO from the Moon may be less costly than launching the propellants from Earth. If the transfer process is very inefficient, it is likely to be less costly to simply deliver propellants to LEO from Earth.

It is implicitly assumed here that accessible water ice can be exploited from polar areas on the Moon. If that is not the case, this entire concept becomes moot. Furthermore, the process may become untenable if the transfer vehicle masses are too high. If these vehicles are too heavy, all the water ice excavated on the Moon would be used to produce $H_2 + O_2$ to deliver the vehicles, and ultimately no net transfer of water to LEO would be feasible. Therefore, it is necessary to examine the details of the transfer process and estimate what percentage of water excavated on the Moon can be transferred to LEO. The percentage of water mined on the Moon that can be transferred from the Moon to LEO for fueling Mars-bound vehicles can be estimated as discussed in Sec. 5.4 of *HMMDR*. The figure of merit is the net percentage of water mined on the Moon that can be transported to LEO for use by Mars-bound vehicles. As this percentage increases, the cost of transporting water to LEO from the Moon becomes more favorable. However, the best estimate is that most of the water excavated on the Moon is used up in transferring the tankers to LEO, and almost no net water is transferred to LEO. This estimate is based on standard spacecraft design principles. On the other hand, if these tanker vehicles can be made much less massive using some unspecified advanced technology, such transfer might one day become feasible.

2.5 Propellants Delivered to Lunar Orbit for Descent (and Ascent)

Whereas the amount of oxygen required for ascent from the Moon is a rather modest ~ 4 mT, the amount of oxygen required for descent is well over 20 mT.[1] If oxygen (and less importantly hydrogen as well) can be delivered to lunar orbit for fueling Moon-bound descent vehicles, the potential payoff from lunar ISRU would be much higher than if lunar

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[1] These propellant masses are based on 2005-6 data. In February 2007, a NASA release indicated that oxygen will not be used for ascent, and over 30 mT of LOX/LH2 will be used for descent. See Reference [1].

ISRU were used only for ascent propellants. The gear ratio (required mass in LEO/mass delivered to lunar orbit) is roughly 2.5. Therefore generation of oxygen via lunar ISRU for use as a descent propellant would save > 55 mT in LEO. The combination of lunar ISRU-provided ascent and descent propellants (hydrogen + oxygen) would save more than 80 mT in LEO, and this mass saving is likely to increase if vehicles become more massive. The concept would then be as follows:

NASA would begin by establishing an outpost in a shadowed polar area of the Moon to excavate regolith, extract water, and to some extent, electrolyze water and store hydrogen and oxygen. This would have to be done robotically without crew participation. Is this possible? Who knows?

NASA would design and implement a tanker system for transferring water from the surface of the Moon to lunar orbit, and establish a filling station in lunar orbit to electrolyze water and fill tanks on incoming vehicles with hydrogen and oxygen. This tanker system would act as a shuttle to move back and forth between the lunar surface and lunar orbit, carrying full tanks on the way up and empty tanks on the way down. The percentage of water extracted on the lunar surface that can be delivered to lunar orbit (after providing propellants for descent of the empty tanker) was estimated in Sec. 5.5 of *HMMDR*.

Incoming LSAM vehicles on their way to the surface of the Moon would carry empty ascent and descent tanks, and would be fueled in lunar orbit prior to descent. In case of an unexpected problem, the crew could return in the CEV and never descend in the LSAM.

However, as in the case of lunar ISRU providing only ascent propellants, this > 80 mT reduction will not be realized in terms of reduced launch vehicle capability if lunar ISRU is adopted as an afterthought late in the campaign.

2.6 Regolith for Radiation Shielding

Use of regolith piled on top of habitats for radiation shielding is probably a legitimate potential use of in situ resources, but the requirements and benefits require further study. Current habitat designs and plans for installing them on the lunar surface do not seem to be compatible with regolith shielding, nor is it known how to install the regolith.

2.7 Visionary Concepts

Visionaries and futurists have proposed a variety of ISRU applications to produce liquid fuels, metals, plastics, huge fields of solar cells, structural materials and electronics from indigenous resources on the Moon and Mars. It seems likely that such approaches will be relegated to generations beyond providing propellants and life support.

3. Lunar ISRU

3.1 Lunar Resources

There are basically four potential lunar resources:

- Silicates in regolith containing typically > 40 wt% oxygen.
- Regolith containing FeO for hydrogen reduction. FeO content may vary from 5 wt% to 14 wt% leading to recoverable oxygen content in the 1-3 wt% range.
- Imbedded atoms in regolith from solar wind (typically parts per million).
- Water ice in regolith pores in permanently shadowed craters near the poles (unknown percentage but possibly as high as a few percent in some locations).

3.2 Lunar ISRU Processing

3.2.1 Oxygen from FeO in Regolith

Hydrogen reduction of regolith depends on the reaction of hydrogen with FeO in the regolith to produce iron and steam [$FeO + H_2 = Fe^0 + H_2O$]. The non-FeO fraction of the regolith does not enter into the reaction. The water (steam) produced in the reactor (at ~ 1300 K) is subsequently separated by condensation and then electrolyzed. The oxygen is collected and saved while the hydrogen is recirculated. Some make-up hydrogen will be needed, as this process will not be 100% efficient. It is not clear how the regolith is fed into the reactor and withdrawn from the reactor. It is also not clear how one prevents "gunking up" within the reactor. Some heat recuperation can be accomplished by using heat from steam and perhaps spent regolith to pre-heat incoming regolith, but those measures will add complexity (and mass) to the process.

The expected recoverable oxygen (in wt%) from a given mass of lunar regolith varies with FeO content from 3% in Mare regions to about 1% in highlands. The projected power requirements to produce oxygen from lunar mare, assuming that solar power is used and that the duty cycle for the process is 40% (3500 hours of processing per year), are given in the following table (assuming 50% heat recovery and linear scalability):

Annual Oxygen Production Rate (mT) ⇒	**1**	**10**	**50**	**100**
Annual regolith rate (mT)	34	336	1,681	3,361
1000s of kWh	5.1	51	255	510
Hours	3,500	3,500	3,500	3,500
kW to heat regolith	1.44	14.4	72	144

The technical and economic feasibility of this process has yet to be demonstrated, although recent pilot plant tests have shown that the reaction can be made to proceed.

3.2.2 Oxygen from Regolith Silicates

Lunar ISRU based on extraction of oxygen from regolith has two advantages compared to reduction of FeO:

(1) Regolith is typically > 40% oxygen.

(2) Regolith is available everywhere and solar energy may be feasible for processing.

Unfortunately, the oxygen in regolith is tied up in silicate bonds that are amongst the strongest chemical bonds that are known, and breaking these bonds inevitably requires very high temperatures and energy inputs.

JSC has investigated several processes for extracting oxygen from lunar silicates. One is the carbothermal process. This concept is based upon a high-temperature, direct energy processing technique to produce oxygen, silicon, iron, and ceramic materials from lunar regolith via carbonaceous high-temperature (carbothermal) reduction at ~ 2600 K. To prevent destruction of the container, they apply heat to a localized region of regolith and the surrounding regolith acts as an insulating barrier to protect the support structures. The plan is to use a set of solar parabolic dish concentrators to beam light directly onto the regolith in the carbothermal reduction cells. Methane gas is introduced into the reduction chamber to provide a source of carbon and hydrogen to scavenge oxygen. According to JSC:

"The lunar regolith will absorb the solar energy and form a small region of molten regolith. A layer of unmelted regolith underneath the molten region will insulate the processing tray from the solar energy. Methane gas in the reduction chamber will crack on the surface of the molten regolith producing carbon and hydrogen. The carbon will diffuse into the molten regolith and reduce the oxides in the melt while the hydrogen gas is released into the chamber. Some hydrogen may reduce the iron oxides in the regolith to form water, which will be recovered by the carbothermal system. A moveable solar concentrator will allow heating in the form of a concentrated beam on the regolith surface. A system of fiber optic cables will distribute the concentrated solar power to small cavities formed by reflector cups that concentrate and refocus any reflected energy. Solidified slag melts are removed from the regolith bed by a rake system. Slag waste and incoming fresh regolith are moved out or into the chamber through a double airlock system to minimize the loss of reactive gases."

This far-fetched scheme would be a nightmare to carry out on Earth. On the Moon, it would be far worse. Preliminary testing has not produced any encouraging results. In the extremely unlikely case that a high-temperature processor for oxygen from regolith on the Moon can be made into a practical unit, one would still be faced with the challenges (and costs) for development and demonstration of autonomous lunar ISRU systems for excavation of regolith, delivery of regolith to the high-temperature processor, operation of the high-temperature processor with free flow of regolith through it (without caking, agglomeration and "gunking up" of regolith), and removal of spent regolith from the high-temperature processor to a waste dump.

3.2.3 Extracting Volatiles

Analysis of lunar rocks from the Apollo missions indicated that heating of the lunar rocks evolved a variety of volatile materials. Hydrogen and nitrogen were reported to be present at the concentration of 10-20 ppm.

Based on this, JSC is seriously considering the prospect of extracting hydrogen for use as a propellant, and nitrogen for use as an oxygen diluent in breathing air – assuming "a best case scenario" that these putative volatiles are available at the 150 ppm level. It is assumed that the volatiles will be released when the regolith is heated to ~ 800 K. Assuming that the regolith starts at say, 200 K, this involves raising the temperature of the regolith by 600°C.

JSC has developed several fanciful concepts for implementing this process. One conceptual process uses "a large inflatable dome that has a center-driven scraper-wand similar to an agricultural silo top-unloading device." The scraper moves in a circular sweep and the regolith is directed by a sort of Rube Goldberg arrangement to a ramp where it is heated by IR or microwave heaters. Evolved volatiles are collected by means of either a cryocooler (for N_2) or a hydride bed (for H_2). However, hydride beds are notorious for being easily poisoned by impurities requiring extremely pure H_2 to operate. The need for nitrogen for a crew of four would be about

4,380 kg/year assuming 3 parts nitrogen to one part oxygen in breathing air. The need for hydrogen for ascent propulsion would be about 1,130 kg/year to go along with 7,350 kg of oxygen.

Assuming more realistic volatile concentrations of 20 ppm, it follows that in order to produce 4,380 kg of nitrogen per year, one must process 2.19×10^8 kg/yr of regolith. Assuming solar availability at 50%, leading to reactor duty cycle ~ 40%, the requirement is for heating 63,000 kg/hr of regolith from 200 K to 800 K, at a power level of 8.8 Megawatts. Such a power rate would seem to be so high as to make volatile recovery prohibitive.

3.2.4 Polar Ice Deposits

There is limited evidence that suggests that recoverable near-surface deposits of water ice may exist in permanently shaded craters near the lunar South Pole. This resource has the great advantage that removal of water from regolith is a physical (rather than a chemical) process and requires far less energy and much lower temperatures. However, on the negative side, it will take a considerable investment to locate the best deposits of ground ice (if indeed they exist – which still remains to be proven conclusively – and if they are accessible); the percentage of water ice in the regolith is likely to be low, necessitating an extensive prospecting program to find the best, most accessible deposits, ultimately requiring processing a great deal of regolith; excavating ice-filled regolith may prove difficult; the logistics of autonomous regolith delivery, water extraction, and regolith removal from a reactor may prove difficult; and the water extraction process must be carried out in dark permanently shadowed craters, necessitating use of nuclear power or less likely, beamed solar power.

It is difficult to be sure how much, if any recoverable water ice is present, and how deeply buried it is below a putative layer of desiccated regolith. The Lunar Reconnaissance Orbiter (LRO) will use a neutron spectrometer (NS) to locate hydrogen signals at much higher spatial resolution than was possible with the Lunar Prospector.

JSC is considering a rather far-fetched scheme in which regolith is excavated from a dark region of a crater, and processed in the dark to remove water (estimated at 1.5% water ice content) from the regolith. The extracted water is carried by a rover to a solar energy system located on the rim of the crater where the water is electrolyzed to hydrogen and oxygen.

The spent regolith is dumped ~ 100 m distant, and the extracted water is transported ~ 8 km to an electrolysis plant located at a rise on the crater rim where sunlight is available at a putative 70% of the time. Within the crater, all power for excavation, regolith transport, and water extraction is claimed to be nuclear, but there are no plans for installing a reactor, there couldn't possibly be enough radioisotope thermal generators (RTGs) available to supply this power, and there certainly isn't enough plutonium available to enable such RTGs to be built. Driving water across a crater surface to an electrolysis plant appears to be a grossly inefficient process. The availability of solar energy on the crater rim will depend on the morphology of the surroundings. Whether 70% availability can be achieved is presently unknown.

Overall, the required investment to do prospecting and validation of resources, and development and demonstration of regolith excavation and transport, and operation of a water extraction system, appears to be many billions of dollars. The benefit/cost ratio remains uncertain but it may take many years to "break even" on the investment.

The power requirement to heat the regolith to drive off water was estimated by *HMMDR* to be about 18 kW to produce 10 mT of oxygen per year. This does not include the power required for excavation and hauling 800 mT/year of regolith. This power is needed in the dark. The much greater power to electrolyze the water could presumably be supplied by solar energy.

3.3 The Campaign for Lunar ISRU

Unfortunately, NASA has not adequately defined the campaign for prospecting, demonstrating and implementing lunar ISRU. Note: in the present context "lunar ISRU" is restricted to oxygen (and possibly hydrogen) production, mainly for ascent propellants. While JSC has plans for manufacturing spare parts on the Moon, producing silicon solar cells on the Moon from regolith, beaming power back to Earth, and extracting parts per million of solar-wind deposited atoms, such work is (fortunately) not yet funded even though it is described in JSC project plans.

Both JSC and ESAS appear to have simplistic notions regarding requirements to prospect for polar ice resources and demonstrate ISRU systems, which will not hold up to any serious scrutiny.

A campaign is an end-to-end sequence of missions and programs to accomplish a goal [5]. My view of the first five steps of the required campaign for developing lunar ISRU based on polar ice is as follows:

[1] The Lunar Reconnaissance Orbiter (LRO) will use a neutron spectrometer (NS) to locate hydrogen signals at high resolution.

[2] Several long-distance rovers equipped with dynamic active neutron spectrometers must be sent to several craters identified by LRO to map out local water ice deposits and estimate vertical distribution.

[3] From the results of [2], rovers would be sent to the most promising site equipped with a drill and excavation equipment to: (a) map out the site with NS in great detail, (2) take subsurface samples to validate rover-mounted dynamic active NS measurements of water-equivalent content, (3) determine the actual form of hydrogen-containing compounds - which are almost surely dominated by water, (4) extract water from some samples and determine the water purity and the potential need for purification, and (5) determine the soil strength and requirements for excavation of the site.

[4] Develop a ~1/10 scale lunar ISRU demonstration system for use at this site, deliver it with human oversight, get it started, and leave it to operate autonomously.

4. Mars ISRU

4.1 Timeline for ISRU on Mars

Launch opportunities to send vehicles to Mars are spaced at roughly 26-month intervals. The ISRU system would be launched ~ 26 months prior to departure of the crew from LEO. The cargo delivery will take about 9 months to get to Mars and perhaps a month to set up operations on the surface. Therefore, ISRU operations could begin ~ 10 months after launch. We would then have 16 months until the crew launches, and about 22 months until the crew arrives at Mars (assuming the crew transits via a fast ~ 6-month trajectory). The full mission timeline is shown in Fig. 1.

The ISRU system could be sized to fill the MAV tanks in 16 months to assure that they are full prior to crew departure from Earth.

The situation for life support is less certain. The ~ 100 mT of water needed on the surface has a volume ~ 100 m^3. It may be possible to store this amount of water in an inflatable tank, and let it freeze. Alternatively, it may be permissible to only extract (from regolith) and store some fraction of this during the 16 months prior to crew launch. The requirements for oxygen and buffer gas (e.g. nitrogen) for a crew of 6 over 600 days are about 3.6 and 10.8 mT, respectively. One might not want to store all the needed buffer gas, and buffer gas might be recycled. As in the case of water, it will have to be decided whether to make all of the oxygen prior to human departure from Earth and then be faced with the problem of storing that large amount, or whether to be content with producing only part of the needed supply prior to crew arrival.

The decision regarding a strategy for production of propellants and consumables requires further thought regarding mass, volumetric and safety/risk considerations as well as power level. The most conservative approach would be to assume that the ISRU system would be sized so that all ascent propellants are produced in 16 months, so that the MAV tanks are full when the crew departs from Earth. The amount of life support consumables to be produced prior to crew departure from Earth remains open to question.

In regard to power, we first need to estimate power requirements for the ~18 month period during which the humans are on the Mars surface, assuming that ISRU operations stop or are significantly reduced when humans arrive. This sets the minimum power level needed for the mission. If this same power level can supply the power needed for ISRU during its 16-month operational period, then it is fair to claim that the mass of the power system is attributable only to human support, and no mass (or cost) attribution for power is made to the ISRU system. If ISRU processing continues while humans are on the surface, the additional mass (and cost) required to scale up the power system beyond human support requirements must be attributed to ISRU.

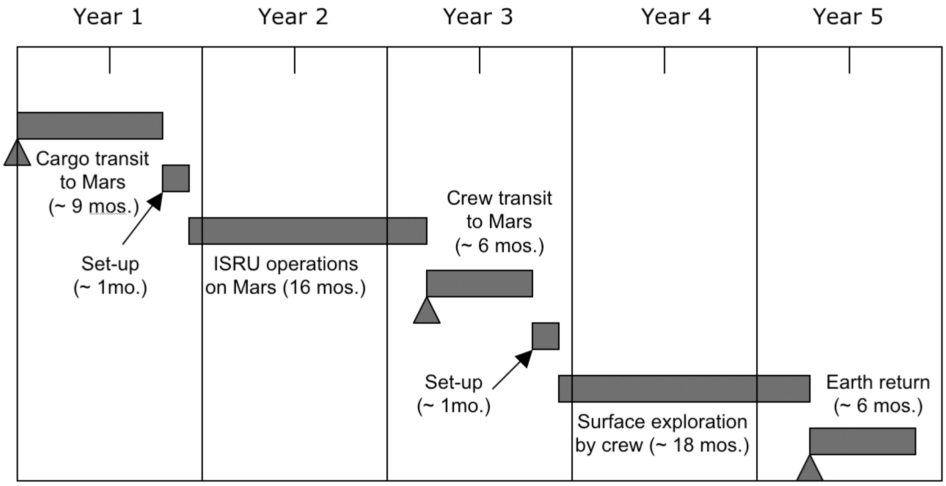

Fig. 1. Hypothetical timeline for a Mars mission utilizing two launch periods and ISRU. Triangles represent departure dates.

A likely scenario (though by no means the only one) is that during the 16-month period of intense ISRU operations prior to crew departure from Earth, the ISRU system will produce the requisite amount of methane and oxygen for ascent, and store these as cryogenic liquids in the tanks of the ascent vehicle. There will be a gradual rate of boil-off of these propellants due to heat leaks into the tanks, unless zero boil-off techniques are used, with a consequent increase in mass, power and complexity. Therefore, it will be desirable to operate the ISRU plant in a greatly reduced mode while the crew is in transit to Mars (and after they land as well) to replenish boil-off. Alternatively, additional propellant tanks could be stored on Mars to hold extra propellants that could be piped to the Mars ascent vehicle prior to ascent to "top-off" the propellant tanks.

4.2 Mars Resources

4.2.1 The Mars Atmosphere

The atmosphere of Mars is ~ 95% CO_2, with the remainder made up mainly of Ar and N_2, and smaller amounts of CO and O_2. The CO_2 is a feedstock used to produce oxygen, and possibly hydrocarbon production if hydrogen is available. Atmospheric pressure varies with hour and season but is typically a bit less than 1/100 of the atmospheric pressure on Earth. Water has been detected in the top ~ 1 m of Mars subsurface by orbiting instruments, and is widely distributed on Mars, particularly at higher latitudes.

4.2.2 Transporting Hydrogen to Mars

Most of the studies and analyses of human missions to Mars were conducted prior to the discovery of widespread near-surface water deposits on Mars. Therefore, they depended on transporting liquid hydrogen from Earth to Mars as a feedstock to react with Martian CO_2 in ISRU processing. These included the JSC mission studies known as DRM-1 and DRM-3 and Bob Zubrin's Mars Direct.

HMMDR presented a detailed review of various options for hydrogen storage. For transport to Mars, storage as a cryogenic liquid seems to be the only approach worth considering. The rate of boil-off from tanks insulated with multi-layer insulation (MLI) can be roughly estimated but this depends on the surroundings. A tank that would be earmarked for landing on Mars would undoubtedly be mounted inside an aeroshell en route to Mars. Configurations that are planned for landing on Mars would likely use a number of smaller tanks for packing density, rather than one large tank, and this would increase the ratio of area to volume compared to one large tank. In addition, the realistic insulating properties of MLI can differ significantly from those measured in the laboratory due to handling, connections and seams.

A number of papers on hydrogen storage were reviewed, and there is some diversity of opinion as to what level of boil-off may be achievable with a passive storage system. One can (at least in principle) keep adding layers of MLI, but there is bound to be a region of diminishing returns where penetrations, connections, seams, and handling factors lead to an asymptotic plateau for high numbers of layers. It appears that such a plateau may be in the range 2-7% per month boil-off in the real world, but it is difficult to fix the boil-off range any more precisely.

Because of the ~9-month trip time to get to Mars, and the fact that the hydrogen tank would be imbedded within an entry aeroshell, boil-off in transit to Mars is a much more serious problem than for the Moon. Nevertheless, it may be possible to transport hydrogen to Mars, arriving with partly empty tanks. For a 9-month cargo transit, clearly there is large difference between 2 or 3% per month and 7% per month boil-off rates for passive storage systems. Alternatively, a zero boil-off (ZBO) system might be effective, but this would add complexity and risk. Depending on the rate of heat leak, the power requirement might be excessive.

But aside from the problem of transporting hydrogen to Mars, an even bigger problem is storing it on the surface of Mars where MLI is ineffective and other insulation systems are much less effective than MLI would be in a high vacuum. To avoid a lengthy storage time for hydrogen on Mars, Robert Zubrin has suggested an ISRU process that uses up the hydrogen rapidly via the Sabatier reaction (which is exothermic) and storing methane and water until the water can slowly be converted to oxygen via electrolysis. However, Zubrin's scheme, though ingenious, requires acquisition of a huge amount of CO_2 in a short time which requires significant power, and other volumetric and logistic challenges in which hydrogen, oxygen and methane would be moved around from tank to tank.

Acquisition of hydrogen from Martian water appears to be eminently more feasible than bringing hydrogen from Earth.

4.2.3 Water on Mars

Water on Mars is a broad topic that is reviewed in Appendix C (55 pages) of *HMMDR*. The conditions under which near-surface subsurface ice may exist in equilibrium with the atmosphere on Mars have been modeled by a number of prominent Mars scientists for forty years, and similar results have been obtained by all. The prediction is that subsurface ice is stable in the pores and interstices of Martian regolith at sufficiently high latitudes. Obviously, subsurface ice is stable at, and just below the surface in polar regions. At lower latitudes, an "ice table" forms in which a desiccated regolith covers an ice-filled layer with the depth of the ice table increasing with decreasing latitude. At some latitude near 55-60° (or perhaps as low as 45° depending on soil properties and slope), the ice table may be 1-3 meters down. At lower latitudes the depth of the ice table increases sharply and at latitudes less than typically ~ 55°, subsurface ice is not thermodynamically stable relative to sublimation to the atmosphere. These are equilibrium models and they do not preclude the possibility of non-equilibrium ice from previous epochs that is very slowly disappearing in regions where ice is not thermodynamically stable.

The Mars Odyssey neutron spectrometer has been used to scan the upper ~ 1 m layer of the Mars surface in elements 5°×5° latitude × longitude. These data support the predictions of models for latitudes > ~55°. High water concentrations are detected with apparent shallow ice tables approaching the surface toward the poles.

In the region of latitude from -45° to +45°, it is found that there is a residual water content that never drops below ~2%, probably representing chemically bound water in the minerals of the soil. In various localized areas within this region, the measured water content in the top 1 m can reach as high as 8 to 10%. Comparison of fast neutron data with epithermal neutron data suggests that there is an upper layer that is desiccated, with a higher water content layer below it. The thickness of the desiccated layer is suggested to be > 20-30 cm.

The localized equatorial regions with relatively high water content (8-10%) present an enigma. On the one hand, thermodynamic models predict that subsurface ice is not stable near the surface in the broad equatorial region. On the other hand, some aspects of the Odyssey data are suggestive of subsurface ice. It is possible that this is metastable subsurface ice left over from a previous epoch with higher obliquity. Alternatively, it could be soil heavily endowed with salts containing water of crystallization. The fact that these areas overlap somewhat with regions of high albedo and low thermal inertia suggest that it is indeed subsurface ice. Furthermore, the pixel size of Odyssey NS data is large, and the 8-10% water figure might represent small local pockets of higher water concentration (where surface properties and slopes are supportive) scattered within an arid background. Over the past million years, the obliquity, eccentricity and precession of the equinoxes of Mars has caused a variable solar input to the planet in which the relative solar input to high and low latitudes has varied considerably. It is almost certain that ground ice was transferred from polar areas to temperate areas during some of these epochs. It is possible that some of this ground ice remains today even though it is thermodynamically unstable in temperate areas. In order for remnant subsurface ice from past epochs to be a proper explanation, the process of ice deposition must be faster than the process of ice sublimation in the temperate areas over time periods of tens or hundreds of thousands of years

We have one data point at the poles. We need ground measurements of ice content down to a few meters at latitudes in the 45-65° range to confirm the predicted ice table.

We need exploration in the 8-10% water equatorial regions to determine the state of the water in these areas because they are regions where ISRU processing is likely to be most efficient. The first step could be improved spatial resolution of orbital observations. Eventually, a landed mission is needed for ground-truth.

Deep within the interior, the temperature will rise to the point where liquid water could exist. Presently, there is no convincing evidence that it does. If liquid water exists deep within Mars (down several km), then the water vapor rising from this liquid water will pass through porous regolith at sub-freezing temperatures. Hence you cannot have liquid water at depth unless there is a huge thick layer of ice-filled regolith above it.

The crater record suggests that the interior of Mars down to several km is mainly filled with H_2O. The connection of this reservoir to near-surface H_2O has not yet been adequately investigated.

We may conclude that a near equatorial mission to Mars can chose a landing site where local water concentration in the upper meter of soil greater than 10%, and possibly much greater than 10%.

4.3 Mars ISRU Processes

4.3.1 CO_2 Acquisition From the Mars Atmosphere

All of the Mars ISRU systems that have been proposed require a supply of relatively pure, pressurized CO_2 from the atmosphere. Since the atmospheric pressure on Mars is typically about 6 torr, it is desirable to compress this by at least a factor of ~ 100 to obtain reasonable throughput in small vessels. These ISRU systems therefore implicitly utilize a subsystem that sucks in dust-free atmosphere, separates the CO_2 from other atmospheric constituents, and compresses the CO_2. (In this process, a limited amount of Ar + N_2 may be obtained as a by-product).

One approach for pressurizing atmospheric CO_2 is a sorption compressor that contains virtually no moving parts and achieves its compression by alternately cooling and heating a sorbent material that absorbs low pressure gas at low temperatures and drives off high pressure gas at higher temperatures. [6] By exposing the sorption compressor to the cold night environment of Mars (roughly 6 torr and 200 K at moderate latitudes), CO_2 is preferentially adsorbed from the Martian atmosphere by the sorbent material. During the day, when solar electrical power is available, the adsorbent is heated in a closed volume, thereby releasing almost pure CO_2 at significantly higher pressures for use as a feedstock in a reactor. A thermal switch isolates the sorbent bed from a radiator during the heating cycle. However, the energy required to heat up the sorbent is significant, and cooling down the sorbent overnight has been shown to be problematic. A large mass and volume of sorbent is needed.

An alternate approach for compression and purification of CO_2 was developed by a team led by Larry Clark at Lockheed-Martin that appears to be superior in that it requires less energy, less mass and less volume. [7] This approach is a cyclic batch process in which the first cycle is freezing out solid CO_2 (using a mechanical cryocooler) on a cold surface while atmosphere is continuously blown over the surface. After a time, sufficient solid CO_2 builds up, and the chamber is closed off from the atmosphere. The chamber is then allowed to warm up passively, which causes the CO_2 to sublime, producing a high gas pressure in the chamber. This high-pressure CO_2 can then be vented to a larger accumulation chamber in which successive inputs of CO_2 will gradually build up the pressure. Because N_2 and Ar remain as gases at CO_2 solidification temperatures, and therefore pass out through the exit of the chamber during acquisition, relatively high-purity CO_2 is produced in this process. A Lockheed-Martin prototype test produced very encouraging results. Unfortunately, NASA does not seem to have funded any further development of this process since 2001.

4.3.2 Oxygen-Only Processes

Several schemes have been proposed for producing propellants from the Mars atmosphere. One approach utilizes only the CO_2 in the Mars atmosphere and produces only O_2 via the reaction

$$2CO_2 \Rightarrow 2CO + O_2 \qquad [1]$$

The two most developed concepts for utilizing Martian CO_2 are (1) Zirconia solid-oxide electrolysis process (SOE), and (2) the Reverse Water Gas Shift (RWGS) developed at Pioneer Astronautics.

Solid Oxide Electrolysis

Solid oxide electrolysis (SOE) is based on the very unusual and unique electrical properties of some ceramics that conduct electrical current using oxygen ions (O^{--}) as the charge carrier rather than electrons. Typically, a solid state yttria stabilized zirconia (YSZ) ion conductor is used. The doped crystal lattice contains "holes" allowing ions to move through the lattice when an electric field is applied across it. The electric field is generated by mounting porous platinum electrodes on each side of a zirconia wafer, and applying a difference in potential. In a zirconia cell, hot CO_2 is brought into contact with a catalyst on the cathode, thus causing some dissociation. Oxygen atoms in contact with the cathode pick up electrons to form O^{--} that are transported through the zirconia to form pure oxygen on the other side at the anode. YSZ has been under study for more than twenty years. The performance increases over the temperature range 800°C to 1000°C, so the materials of all cell components are critical, and sealing the edges is difficult, particularly when the cell must be repeatedly thermally cycled through many cycles. For a system that can produce, say, 4 kg/hr of O_2, the required ion current is 12,300 amps. Typical current densities on YSZ disks range from 0.3 to 0.5 amps/cm^2. For a value of say 0.4 amps/cm^2, the required area of zirconia wafer is about 30,750 cm^2. If a zirconia disk is as large as say, 5 cm x 5 cm square, its effective transport area is around 20 cm^2. This would imply that roughly 1,540 wafers of this size are needed for a full-scale unit. Thus a full-scale system will require many zirconia wafers connected in series in “stacks." Several investigators have built and tested single YSZ flat disk designs, but these cannot provide the required YSZ surface area in a small volume. A "stack" of YSZ disks is needed to produce a significant flow rate of oxygen.

The power requirement for the zirconia stack depends upon the voltage required to drive the ion current through the YSZ. It is found experimentally that as the temperature and voltage are raised, the current density (amps/cm^2) increases. This allows use of less YSZ area, which leads to a more compact cell. However, as the temperature is increased, the problems of sealing and withstanding thermal cycling increase.

Relatively little work has been reported on use of YSZ stacks, but it appears that sealing problems are very challenging. Whether a workable robust multi-wafer cell can ever be produced remains doubtful.

The Reverse Water Gas Shift Process

Robert Zubrin has made a number of innovations in ISRU technology. One of these is the development of the Reverse Water Gas Shift (RWGS) Process. [8]

The water-gas shift reaction is widely used by industry to convert relatively useless $CO + H_2O$ into much more useful hydrogen. However, if reaction conditions are adjusted to reverse the reaction so it has the form:

$CO_2 + H_2 \Rightarrow CO + H_2O$ (catalyst required) [2]

then CO_2 can be converted to water. If that water is electrolyzed:

$2H_2O + \text{electricity} \Rightarrow 2H_2 + O_2$ [3]

the net effect of the two reactions is conversion of CO_2 to O_2 (Reaction [1]). Ideally, all the hydrogen used in the first reaction is regenerated in the electrolysis reaction, so no net hydrogen is required. Actually, some hydrogen will be probably be lost if the first reaction does not go to completion, although use of a hydrogen recovery membrane can minimize this loss. The above two reactions in concert represent what is referred to as the "reverse water-gas shift" (RWGS) process.

Note that the reagents for the RWGS reaction are the same as for the S/E reaction (see next section). The main difference (aside from use of a different catalyst) is that the S/E process has a favorable equilibrium at lower temperatures (200 - 300°C) while the RWGS has a more favorable equilibrium at much higher temperatures (> 600°C). If one considers the combined equilibria where catalysts are present which allow both reactions to take place, the S/E process will be dominant below about 400°C, and the reaction products will be mainly $CH_4 + 2H_2O$. At temperatures above about 650°C, methane production falls off to nil and the RWGS products ($CO + H_2O$) are dominant. Between about 400°C and 650°C, a transition zone exists, where both reactions take place. In this zone, CO production rapidly rises as the temperature increases from 400°C to 650°C while methane production falls sharply over this temperature range. However, in the RWGS regime, no matter how high the temperature is raised, roughly half of the CO_2 and H_2 remain unreacted.

At lower temperatures (200-300°C), equilibrium would dictate that almost all the hydrogen is used up to produce methane and water, and the excess carbon dioxide is depleted by an equivalent amount. This is the S/E region. Almost no CO is formed. By contrast, at high temperatures (> 650°C) CO and H_2O are the principal products, and very little methane is formed, but roughly half of the initial carbon dioxide and hydrogen remains unreacted in the product stream. If one attempted to run the RWGS reactor at say, 400°C, Reaction [2] would only go about 25% to completion. Despite the unfavorable equilibrium, Zubrin and co-workers have suggested several methods to force Reaction [2] to the right, even at 400°C. These include:

(i) Water condensation to water vapor pressure and recirculation of CO + CO_2 (water produced by the RWGS reaction is condensed out downstream of the reactor and resultant gases are recirculated with continuous mixing of a smaller flow of feed gases).

(ii) Use of excess hydrogen (off-stoichiometric mixtures) to force the reaction to the right, with membrane recovery of unreacted hydrogen fed back into reactants.

(iii) Increasing the reactor pressure.

Using these techniques, Zubrin reported high conversion efficiency in a breadboard system. It remains to be seen how efficient and practical this system will be when further developed. NASA does not seem to have funded further development of this process after about 1995. In the field of ISRU, the reward for good work seems to be a cutoff of funding.

4.3.3 The Sabatier/Electrolysis Process

Another approach utilizes both CO_2 from the Mars atmosphere and hydrogen (brought from Earth or produced from Mars water deposits) – the Sabatier/Electrolysis (S/E) process. In the S/E process, hydrogen is reacted with compressed CO_2 in a heated chemical reactor:

$$CO_2 + 4\ H_2 \Rightarrow CH_4 + 2\ H_2O \text{ (catalyst)} \qquad [4]$$

The reactor is simply a tube filled with catalyst. Since the reaction is exothermic, no energy has to be supplied once the reaction is started.

The methane/water mixture is separated in a condenser, and the methane is dried, and stored for use as a propellant. The water is collected, deionized, and electrolyzed in an electrolysis cell:

$$2H_2O + \text{electricity} \Rightarrow 2H_2 + O_2 \qquad [5]$$

The oxygen is stored for use as a propellant and the hydrogen is recirculated to the chemical reactor. Note that only 1/2 as much hydrogen is produced by reaction [5] as is needed for reaction [4], showing that an external source of hydrogen is necessary for this process to work.

It has been found experimentally that at a reactor pressure of the order of ~ 1 bar, if a mixture of CO_2 + $4H_2$ enters a packed bed of catalyst, a temperature near ~300°C is high enough to approach equilibrium in a small reactor, and the equilibrium is far enough to the right that yields of over 90% $CH_4 + 2H_2O$ are obtained. If the exit zone of the reactor is allowed to cool below 300°C, the yield can be > 95%. [9]

A problem with the S/E process when used with a hydrogen feedstock; namely that it produces one molecule of methane for each molecule of oxygen, while the ideal mixture ratio for propulsion is roughly one molecule of methane for each 1.75 molecules of oxygen. Thus, there is an excess of methane for the amount of oxygen produced. This in itself is not so fundamentally bad, except that it requires that we must transport extra hydrogen to Mars to create this wasted methane. Several schemes have been proposed to recover hydrogen from excess methane, and in addition, other methods for reducing the required amount of hydrogen have been proposed by converting to higher hydrocarbons with higher C/H ratios than methane. These processes are undeveloped and are probably not needed since indigenous Mars water is likely to be used as the source of hydrogen. It has also been proposed that storage of cryogenic methane could be simplified by conversion to methyl alcohol, [10] but since cryogenic oxygen must be stored anyway, this appears to have only a minor benefit.

4.3.4 Mass and power requirements of a Mars ISRU system

A joint JPL-Lockheed-Martin Study in 2004-5 (to be referred to as "*JPLMS*") [11] modeled an ISRU system that utilized the following elements:

- Water is obtained from near-surface regolith containing ~ 10% water by weight.
- CO_2 is acquired by a cryogenic freezing process.
- The Sabatier-Electrolysis process is used.
- ISRU is carried out in a 16-month cycle to produce 10 mT of CH_4, 35 mT of propellant oxygen, 5 mT of consumable oxygen, and 108 mT of water.
- Propellant tank masses are not included in the ISRU system mass because they are needed as part of the MAV, with or without ISRU. Requirements for maintaining CH_4 and O_2 as liquids in the MAV are also attributed to the MAV, not to ISRU. However, the one-time requirement to liquefy the gases produced by ISRU is attributed to the ISRU system.

The *JPLMS* estimated the mass and power requirements for various steps as shown in Table 1.

Table 1. Estimated gross mass and power requirements for various Mars ISRU process steps.

Process Step	Total feedstock used in 16 mos.	Feed-stock rate (kg/hr)	Mass of unit (kg)	Power required (kW)
H_2O acquisition	22,500 kg H_2O	2.0	3000	24
CO_2 acquisition	27,500 kg CO_2	2.4	120	2.9
Sabatier conversion	27,500 kg CO_2	2.4	30	0.4
Water electrolysis	33,750 kg H_2O*	2.9	33	7.0
Liquefying O_2	35,000 kg O_2	3.0	105	3.3
Liquefying CH_4	10,000 kg CH_4	0.87	74	2.6
TOTAL			**3360**	**40.2**

* In addition to 22,500 kg of water feedstock, an additional 11,250 kg of recycled product water from the Sabatier process must be electrolyzed.

Allowing for inefficiencies, we should probably increase the figures in this table by at least 15-20%.

It should be noted that we have assumed that the ISRU system functions 24/7 for sixteen months and thus a relatively small system produces a huge amount of product. For example, regolith excavation is only about 20 kg per hour (or 10 liters of volume per hour) to produce 2 kg/hr of water. Note that the ISRU system mass is dominated by excavation systems.

4.4 Summary

ISRU on Mars has significant advantages compared to lunar ISRU:

- The gear ratio for delivery of assets from LEO to the Mars surface is higher than for the lunar surface, thus requiring more IMLEO per unit mass delivered to the surface of Mars. This, in turn, makes mass replacement on Mars by ISRU more valuable than mass replacement by ISRU on the Moon.
- The Δv for ascent from the Mars surface to orbit is much greater than Δv for ascent in the lunar case, necessitating much greater propellant requirements for ascent. This, in turn, makes propellant production on Mars by ISRU more valuable than propellant production by ISRU on the Moon.
- By placing the Earth Return Vehicle (ERV) in an elongated elliptical orbit (in the Mars case) one can increase the required Δv for ascent (and thereby the amount of ascent propellants supplied by ISRU) while decreasing the Δv requirements for orbit insertion of the ERV (propellants supplied from Earth) as well as for Earth return from Mars orbit. As it turns out, the mass savings by allowing the ERV to utilize

an elliptical orbit are even greater than the mass saving due to reduced mass delivered to the Mars surface.

- The combination of the previous three points provides much greater mission impact (IMLEO reduction) for in situ production of ascent propellants on Mars than on the Moon.
- Because of the long round trip to Mars (~ 2.7 years), total consumption of life support consumables amounts to perhaps 200 mT. It is not clear whether an ECLSS system will have the longevity to provide fail-safe performance over that time period. Such an ECLSS system to provide air and water (if it is feasible) is likely to weigh > 30 mT.
- Unlike the Moon, Mars has a ready supply of carbon and oxygen in the easily acquired atmosphere.
- Unlike the Moon, Mars has significant near-surface deposits of water (believed to be mainly in the form of ground ice) widespread across much of the planet.
- The combination of atmospheric CO_2 and water from regolith provides feedstocks on Mars that enable proven, relatively simple Sabatier-electrolysis processing to produce methane and oxygen propellants, and water for life support.
- In conclusion, Mars ISRU is far more easily implemented and has far more mission impact than lunar ISRU.

The major unknowns regarding Mars ISRU are:

- What are the requirements for excavating water-bearing near-surface regolith and extracting water?
- In the case of equatorial water-bearing near-surface regolith, is the water in the form of ground ice or mineral hydrates?

Unfortunately, neither ESAS nor the Mars Exploration (Science) Program appear to have any specific plans to investigate these questions.

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Abbreviations

CEV	Crew Exploration Vehicle
CM	Crew member
DRM	Design Reference Mission
ECLSS	Environmental Control and Life Support System
ERV	Earth Return Vehicle
ESAS	Exploration Systems Architecture Study
HMMDR	Human Missions to Mars by Donald Rapp
IMLEO	Initial mass in LEO
ISRU	In situ resource utilization
ISS	International Space Station
JPLMS	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low Earth orbit
LRO	Lunar Reconnaissance Orbiter
LSAM	Lunar Surface Access Module
MAV	Mars Ascent Vehicle
MIT	Massachusetts Institute of Technology
MLI	Multi-layer insulation

NASA	National Aeronautics and Space Administration
NS	Neutron spectrometer
RTG	Radioisotope Thermal Generator
RWGS	Reverse Water Gas Shift
S/E	Sabatier/Electrolysis
ZBO	Zero boil-off

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