

In-Situ Resource Utilization for Space Exploration: Resource Processing, Mission-Enabling Technologies, and Lessons for Sustainability on Earth and Beyond

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As humanity begins to reach out into the solar system, it has become apparent that supporting a human or robotic presence in transit and/or on station requires significant expendable resources including consumables (to support people), fuel, and convenient reliable power. Transporting all necessary expendables is inefficient, inconvenient, costly, and, in the final analysis, a complicating factor for mission planners and a significant source of potential failure modes. Over the past twenty-five years, beginning with the Space Exploration Initiative, researchers at the NASA Glenn Research Center (GRC), academic collaborators, and industrial partners have analyzed, researched, and developed successful solutions for the challenges posed by surviving and even thriving in the resource limited environment(s) presented by near-Earth space and non-terrestrial surface operations. In this retrospective paper, we highlight the efforts of the co-authors in resource simulation and utilization, materials processing and consumable(s) production, power systems and analysis, fuel storage and handling, propulsion systems, and mission operations. As we move forward in our quest to explore space using a resource-optimized approach, it is worthwhile to consider lessons learned relative to efficient utilization of the (comparatively) abundant natural resources and improving the sustainability (and environment) for life on Earth. We reconsider Lunar (and briefly Martian) resource utilization for potential colonization, and discuss next steps moving away from Earth.

Nomenclature

CI	= generic term for simple one-carbon (CO , CO_2 , CH_4) compounds
CH_4	= chemical symbol for methane
CO	= chemical symbol for carbon monoxide
CO_2	= chemical symbol for carbon dioxide
$CRRM$	= Carbothermal regolith reduction module
$ECLSS$	= Environmental control and life support system
ΔG	= Gibbs free energy change
ΔH	= Enthalpy change, related to Gibbs free energy change: $\Delta G = \Delta H - T\Delta S$
${}^{3,4}He$	= Helium-3 or -4, an isotope of helium determined by total of protons + neutrons
$F-T(S)$	= Fischer-Tröpsch (synthesis)

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H_2	=	chemical symbol for molecular hydrogen
H_2O	=	chemical symbol for water
I_{sp}	=	Specific impulse, a measure of effectiveness of a fuel
<i>ISRU</i>	=	In situ resource utilization
<i>ISS</i>	=	International Space Station
<i>LEO</i>	=	Low-earth orbit
<i>LRR</i>	=	Logistics reduction and repurposing
<i>NTP</i>	=	Nuclear thermal propulsion
<i>PAG</i>	=	Plasma assisted gasification
Re	=	Reynolds number of a fluid flow, related to amount of turbulence
<i>Sabatier</i>	=	Exothermic reaction that reduces CO_2 with molecular hydrogen to CH_4 and H_2O
<i>SBIR</i>	=	Small business innovative research program
<i>Syn-Gas</i>	=	Synthesis gas: Hydrogen/carbon monoxide gaseous mixture, typical ratio is 2-3:1
ΔV	=	Delta-V is related to the relative velocity needed to change trajectories
<i>WTE</i>	=	Waste-to-energy technologies

I. Introduction and Background

AS NASA moves forward with plans to support human exploration of the solar system, a critical need arises to supply basic materials such as oxygen (O_2) and water (H_2O), food, propellants, and other materials (radiation shielding, clothing, etc.).¹ Thus far, exploration has relied on materials brought from Earth; this conservative approach, while quite costly, minimizes risk to crews. As mankind ventures farther from Earth and for greater periods of time, it becomes imperative to develop technologies and mission architectures that utilize local resources such as Lunar regolith or Martian atmosphere, referred to as *in-situ* resource utilization or ISRU.²

Therefore, ISRU is an overall approach for human exploration based upon utilization of scarce resources (and anthropogenic material(s)) derived from extraterrestrial bodies (surface and extant atmosphere) including planets, moons, and asteroids. NASA GRC has a twenty-five year legacy in developing technologies to contribute to this technically challenging exploration architecture. The work pioneered and supported by GRC includes concept proposals, mission studies, hardware (including contractor-provided hardware) development, and technology demonstrations to produce propellants (and other expendables) using extraterrestrial resources for the exploration of the Moon,³⁻⁵ Mars,⁶⁻⁸ and beyond.^{9,10}

For sustainability considerations on Earth, efficient utilization of raw materials and energy often involves recycling: re-use or recovery of hydrocarbons (or syn-gas, *vide infra*) from waste plastics;¹¹ another critical concern is production of clean water from salt or wastewater. These can be related back to long-term in-flight or surface-operating utilization of waste and trash to produce essential materials such as water (H_2O), propellants, and O_2 .¹² On a rocky surface, lighter elements such as O_2 , nitrogen (N_2), and particularly carbon and hydrogen (H_2) are either not readily available or strongly bonded to metal or metalloid atoms in loose regolith and rocks (especially O_2) requiring significant energy for extraction.³⁻⁵

For a variety of economic, logistical, and technical reasons, transportation fuels production (including aerospace propellants) from non-traditional sources (gases, waste materials, and biomass) has been pursued for decades. These reasons include reducing terrestrial waste streams simultaneous with energy conversion, plentiful biomass, new low-cost methane sources made available by aggressive new extraction methods, and/or in-situ resource utilization of limited resources found in space (or extraterrestrial surface); they each present significant technological and business opportunities being realized by a new generation of visionary entrepreneurs.¹³

From an operational perspective of ISRU, we have explored processing of available resources,^{3,7} use of solar concentrator technologies to process raw materials,^{4,5} and compared methods of production for green aerospace fuels processing¹³ including a preliminary comparison of methods using a two-stage production approach.¹² In this report, we provide a brief retrospective while looking towards the future. The ISRU rationale and paradigm are described; fundamental considerations and mission-enabling technologies are highlighted. Finally, we will discuss a series of issues to be addressed while developing technologies relevant to sustaining life on the Earth, Moon, and beyond.

II. Processing Technologies: Terrestrial Beginnings and ISRU Applications

The concept of “Living off the land” imposes severe constraints for utilization of power, propellants, and other expendables. The normal rigors (mass, space limitations and environmental challenges) imposed by space travel are magnified by a resource-limited situation. On the other hand, enhanced energy efficiency and minimal launch mass will simplify missions (and increase successful outcomes) by resultant limitations to planned activities. Thus the

technical hurdles and challenges alluded to above will stimulate development of technology solutions for space exploration that can be spun off to solve terrestrial problems for defense, dual-use, and commercial transportation, power generation, and efficient resource utilization.¹⁴ This section discusses new technologies and/or applications for materials processing, hardware engineering, and systems integration to enable technological solutions for the challenging technical hurdles of space exploration and green energy conversion.

A. Fuel Production from Alternative Feedstocks: Thermodynamics and Reactors

An important consideration for fuel production from non-petroleum raw materials begins with the energy balance of the chemical reactions at the heart of the various unit operations that comprise the processing steps and related hardware. The enthalpy (ΔH) change is an indication of whether a transformation releases energy (exothermic, negative ΔH) or requires energy input (endothermic, positive ΔH). Depending upon the feedstock and/or desired products, combining endothermic and exothermic reactions minimizes the energy that must be added to the overall system. Several endothermic reactions are available to produce synthesis gas (carbon monoxide (CO) and H₂)¹⁵ or producer gas (includes other gases such as H₂O, O₂, methane (CH₄) and carbon dioxide (CO₂))¹⁶ from steam reforming of coal (1) or biomass (2), or carbon dioxide reforming of methane (3), for example.



This step can be followed by an exothermic reaction to break C-O and H-H bonds, making C-C bonds and C-H bonds such as the Sabatier (equation (4)),¹⁷ methanation (5)¹⁸ or thermodynamically equivalent Fischer-Tröpsch (6)¹⁹ reactions.



Figure 1 shows such an operational system developed by Pioneer Astronautics combining a steam reformer and Sabatier reactor.¹³ Alternatively, a one-step approach can be pursued, typically relying on endothermic processes that can be fueled by heat supplied by combustion of volatile low-carbon by-products (C1-C4) that are not suitable as propellants; see for example Fig. 2 showing an operational thermal cracking or pyrolysis unit developed by RES Polyflow.¹³ These tertiary “cracking” processes are also referred to as chemical recycling¹¹ and are much simpler from a reaction engineering and system perspective but produce relatively large amounts of solid waste or char and are not suitable for a non-terrestrial or minimally-attended environments relevant for space exploration.¹⁻⁸

A third process that captures elements of steam reforming and pyrolysis is flash cracking of plastic waste into tunable molecular weight fuels. This technology, being developed by Aerodyne Research, Inc. “flashes off” desired hydrocarbon products as they form, thus preventing the over-cracking of the polymers into more volatile hydrocarbons.²⁰ Key advantages of this innovation

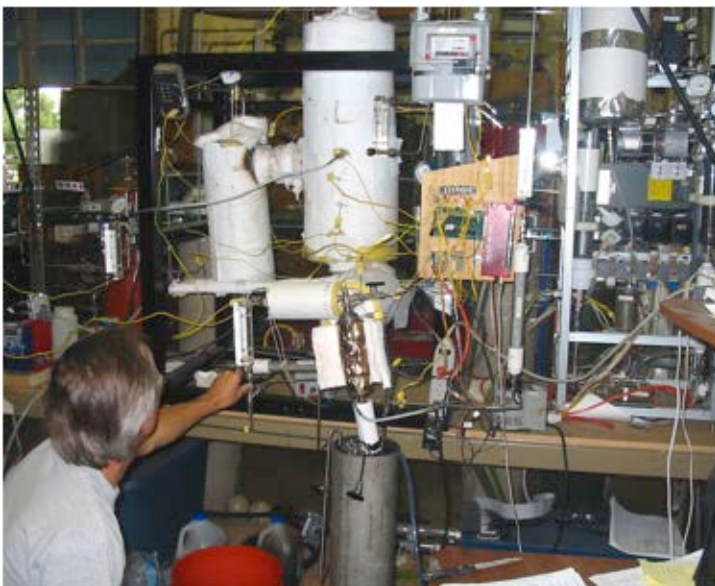


Figure 1. Steam reformer/Sabatier reactor system delivered to GRC from SBIR Phase II contract.

are 1) improved selectivity for low vapor-pressure hydrocarbons, which are easier to store as fuel in large quantities at low pressures; 2) tunable molecular-weight products by changing operating conditions for multiple applications. Promising initial results suggest that this technology can be utilized to produce useful liquid fuels with tunable product distributions. It can also be easily modified for Fischer-Tröpsch wax cracking during Fischer-Tröpsch synthesis to improve its overall conversion.^{15,19}

B. Energy Efficiency Issues and Solar Concentrator Testing in a Simulated Lunar Setting

Energy must be considered at a system level, where where heat is added to the system for driving endothermic reactions ((1) - (3)); heat is subsequently harvested from exothermic reactions ((4) - (6)) for improving overall system efficiency. Overall heat rejection must also be considered. Electric power derived from spacecraft photovoltaics is the most likely source of process energy, including the electrical energy needed for running pumps and splitting water. In certain cases there may be merit in considering solar thermal to augment the process energy, particularly for endothermic reforming reactions.

Given a sun-tracking requirement, solar thermal augmentation may best be suited for treatment facilities that are anchored to the lunar or Martian surface rather than part of a spacecraft rotating about its axis for thermal control. Numerous studies have been completed on the various types of solar thermal concepts available for possible use, ranging from rigid structures having facets with high quality optical surfaces and concentration ratios of the order of 8000:1, to concepts that tout light weight inflatable structures, light pipes, and trough systems with lesser efficiency and lesser concentration ratios.^{5,21,22}

A recent successful demonstration of a solar concentrator for an ISRU-based application involved running a carbothermal reactor in a simulated lunar environment.⁵ The carbothermal reduction method uses a temperature of at least 1800K to extract the oxygen from all the major constituents of the lunar regolith. The carbothermal reactor must melt the regolith to start the reaction; this melt is achieved by heating a small amount of regolith and using the surrounding regolith as insulation. Concentrated solar energy is used to melt the regolith. Excess space above the regolith is used to flow the reacting gas, methane. The gas reacts with the molten regolith to produce water, which is then electrolyzed to produce oxygen and hydrogen. The hydrogen gas is reused in the process to regenerate the methane.

The solar energy is focused through a window into the reactor chamber. There are other methods that could be implemented to focus concentrated solar energy onto the regolith, including heat pipes or fiber optic cables. There are some potential design concerns with each of these approaches. For example by using a window to let concentrated sunlight into the chamber the window could be obscured by regolith particles in the reactor clinging to the window. Also the chamber has free flowing gas, which could pickup dust and interfere with the focusing of the light. It should be noted that a sufficient gap is required between the regolith and the window otherwise, the temperature gradient across the window can cause excessive thermal stresses potentially causing failure. Deposits on the end of the quartz rod will absorb some of the concentrated solar energy, both attenuating the solar energy delivered to the regolith and quickly heating the quartz rod until failure.

An Orbital Technologies Corporation (ORBITEC) Carbothermal Regolith Reduction Module (CRRM) was initially tested with a CO₂ laser to simulate concentrated solar energy.²³ The CO₂ laser energy passed through a zinc selenide (ZnSe) window and illuminated a bed of lunar regolith simulant located at the bottom of the sealed processing chamber within the CRRM. The laser energy absorbed by the regolith simulant caused rapid, localized heating. If laser energy flux was high enough, a pool of molten simulant would form surrounded by un-melted



Figure 2. Commercial pilot-scale reactor for chemical recycling.

simulant due to the low thermal conductivity of regolith simulant. The surface temperature of molten simulant was determined by the laser energy flux. This heating approach worked well as long as the ZnSe laser window remained completely clean during operation. Surface temperatures of the molten regolith simulant in excess of 1800°C were easy to achieve and maintain.

A solar concentrator system developed by Physical Sciences Inc. (PSI) was integrated with the ORBITEC CRRM.²⁴ The integrated system was successfully operated for nearly two weeks during the January 2010 International Lunar Surface Operations and ISRU Analog Test on Mauna Kea in Hawaii shown in Fig. 3. Concentrated solar energy was delivered into the processing chamber through a quartz rod; since the temperature of the regolith surface was determined by the flux of the solar energy, varying the distance of the quartz rod above the regolith controlled the regolith temperature. Similar to the ZnSe laser window, the quartz rod efficiently transmitted the concentrated solar energy into the processing chamber when it was clean. Further development is required to optimize the efficiency of this unit operation.

While use of concentrated solar power for processing of in-situ resources is attractive for lunar installations, Martian applications are less attractive, owing to the greater distance from the sun, the prevalence of dust storms, and wind loading on structures.²⁵ Use of concentrated solar power on a deep space habitat is problematic, given the anticipated rotoisserie motion of the spacecraft needed for thermal control. Autonomous mining of near Earth asteroids is another potential use for concentrated solar power, where core samples carved from an asteroid are directed into a high temperature reactor to recover volatiles. Recovering iron or precious metals may be another possible use for concentrated solar power.

Finally, as we reconsider systems designs, shuttling of excess heat from exothermic reactions to power endothermic reactions may be possible utilizing conventional heat pipes or heat exchangers designed to deliver such energy from one location to another.^{5,21} However, a temperature gradient is needed in such systems, the processing temperatures may limit such a concept, and losses are inevitable. Heat pumps are available to shuttle excess heat from one location to another, with the added feature of increasing the temperature at the outlet. Of course, heat pumps represent an electric load on the system and must be incorporated into any energy balance study. Perhaps the ideal concept is one where sufficient electrical power is provided to the reactor into which reactants are provided to overcome the sensible heat of the reactor mass and the energy needed to initiate endothermic reactions during transient start up operations, and electrical power is throttled back as new solar thermal heat sources are brought on line during steady state operation. Repeated transient and steady state operation should be expected for either batch or continuous processing, though far fewer cycles would be anticipated for a continuous reactor.⁵

C. Transformation of Raw Materials: Cross Fertilization of Terrestrial and ISRU Technologies

There have been numerous excellent reviews that summarize and analyze in detail the various technologies, products, energy balance, and economics of several mainstream terrestrial waste-to-energy (WTE) technologies; relevant reactions can be considered as tertiary (includes larger fragments of C5 or higher) or quaternary processes (for simpler or mainly C1 products).¹¹ For space exploration, NASA's Logistics Reduction and Repurposing (LRR) program addresses a similar technical problem of waste utilization but on a much smaller scale. On a deep space mission, each astronaut will generate a waste stream of about one kg/per day, consisting primarily of organics suitable for decomposition into carbon, oxygen, and hydrogen. In-flight utilization of waste and trash to produce essential materials such as water, fuel(s), and oxygen is an anthropogenic-waste application of an ISRU approach for sustainability. For prudent and efficient utilization of terrestrial raw materials and energy for transportation fuel production, re-use or recovery of



Figure 3. Integrated Carbothermal Regolith Reduction reactor integrated to a solar energy collection and delivery module developed on SBIR contracts – successfully demonstrated on mountainside in Hawaii.

hydrocarbons from waste materials or gas flares is increasingly integrated into process design(s).^{5,11,26}

The LRR program considered a number of processes have been explored for potential use as reactions for the conversion of the waste into useful products, including incineration, steam reforming, pyrolysis, catalytic wet air oxidation, and ozonation.^{12,20} A comparison of relevant technical details as well as energy utilization for several representative processes and suitability for potential use in mobile platforms, terrestrial applications or space missions is detailed in Table 1. The list of processes considered includes primary (more energy intensive) processes such as thermal cracking, flash cracking, steam reforming, and plasma assisted gasification technologies; for comparison, auxiliary processes – photocatalysis²⁷ and catalytic wet air oxidation (CWAQ)²⁸ are included.

Table 1. Comparison of Relevant Metrics for Waste Handling Processes

Process (Type) ^a	Temperature; Pressure (MPa) Range(s)	Product Output	Technical Complexity	Energy Efficiency or Utilization	Appropriate Application(s)
Thermal Cracking (T)	400-450 °C 4-6.9	C1-C5 Mostly > C6 Hydrocarbons	Low	Burning C1-C5 Fraction Supplies 80% Energy	Chemical Recycling Plant
Flash Cracking (T or Q)	400-600 °C 0.1-1.0	Flexible: C1- C10 depending upon T, P, catalyst	Medium	Designed to be Low Energy; Potential Solar Energy Use	Recycling or Mobile/ISRU
Photocatalysis (Q)	25°C 0.1	Oxygenated C1- C5 depends upon time, light energy & photocatalyst	Low ^b	Low Energy; Relies on Solar Energy Use	Municipal water or Auxiliary for ISRU
Catalytic Wet Air Oxidation (Q)	200-350°C 2.0-20	Syn-Gas (CO +H ₂), CO ₂ , CH ₄	Medium ^b	Designed to be Low Energy; Potential Solar Energy Use	Auxiliary process for ISRU
Steam Reforming (Q)	~ 850 °C 0.3-0.7	Syn-Gas (CO +H ₂), CO ₂ , CH ₄	Medium ^b	Balancing Endothermic and Exothermic Reactions	Mobile/ISRU
Plasma Assisted Gasification (Q)	~ 5,000 °C 0.1	Primarily Syn-Gas	High ^b	Recovery of Thermal Energy from > 1000 °C Syn-Gas Stream	Municipal Power

^a – Chemical Recycling (T/Tertiary) or Energy Recovery (Q/Quaternary). ^b – Needs to be combined with a secondary process to produce fuels.

An example of a thermal cracking or pyrolysis chemical recycling technology being developed by (among others) an Akron, OH-based start-up company (RES Polyflow) is shown above in Fig. 2. The RES Polyflow pyrolysis process is quite simple but scalability may be an issue for space utilization. However, an interesting potential application of this technology could be as the key process to enable a fleet of sea-going vessels to collect and process islands of plastic waste or marine litter²⁹ that are currently gathering in various places on the oceans and are thought to pose a potential long-term pollution issue. Using solar thermal and solar electric energy along with selling the chemical feedstocks and fuels produced would defray costs and possibly produce a near break-even or profitable enterprise.

As discussed above, a flash cracking reactor is quite flexible from a process perspective and hence is somewhat similar to FTS, the most flexible of the secondary processes of synthesis or producer gas conversion. The final product mix can be tailored depending upon the temperature and pressure as well as the presence of a catalyst.³⁰ The lower energy demand for this process can be met by solar thermal and photovoltaic sources; this aspect of system design was addressed in a generic sense above.

The steam reforming process can handle a broader (dirtier) feedstock and includes an integrated Sabatier process to produce methane but requires a hydrogen source. Pioneer Astronautics has combined two unit operations that work in tandem to produce methane and oxygen. The process is quite scalable and was delivered to NASA GRC

in Summer 2013 as a prototype unit (Fig. 1) from a Phase II small business innovative research (SBIR) program. One issue is the need for an external hydrogen source for a Sabatier reactor: this would most likely come from splitting water.¹³ But on the whole, steam reforming offers the prospect of significantly reducing the waste plastics derived from LRR.

The rather complex plasma-assisted gasification process relies on high temperatures to recover thermal energies; it is included for the sake of comparison, and is currently only practical for larger-scale (municipal) use. While it is difficult to make direct comparisons regarding scale of infrastructure required, a typical plasma system requires significant balance-of-system hardware in order to enable self-sustaining electrical power. An energy-efficient system will include reusing otherwise wasted thermal energy from stage-one products (i.e. syn-gas at > 1000 °C) to drive turbines to generate electricity. This would then be followed by a F-T operation to convert syn-gas (CO and hydrogen) into a product soup of saturated and unsaturated hydrocarbons as well as some oxygenated products such as alcohols of C5 to C20 or so with some waxy materials. The balance-of-system technology requirements drive up the complexity (and cost), thus minimizing suitability for space applications.³¹

Finally, the Sabatier reaction (4), a century-old CO₂ reduction process,¹⁷ is considered an important part of the architecture for the human exploration of Mars.²⁵ A Sabatier reactor is already part of the environmental control and life support system (ECLSS) equipment on the International Space Station (ISS) to process CO₂, primarily for its removal and water recovery. Utilizing a Sabatier reactor saves considerable mass in water resupply by diminishing the need for water up-mass and substituting a significantly less massive resupply of hydrogen. For ISS, the methane created is jettisoned overboard. However, for a deep space habitat, one could easily envision an additional treatment process where hydrogen is recovered from methane via pyrolysis at 1000 °C. The byproduct of this additional step is pyrolytic graphite that could be utilized as filler or a conductivity-enhancing agent in the printing of composite tools and hardware during a 400-day mission.

III. Saltwater Desalination Using Solar Concentrators: A Terrestrial Case Study

In an effort to provide fresh water through desalination in a clean, economical, and environmentally friendly way, a solar powered water desalination facility was considered. Selling the fresh water produced as well as the left over salt could pay for this facility. With a water production rate of 475,000 gallons per day the possible profit could be \$9 million a year. However, the current costs of the solar concentrators alone were estimated to be over \$260 million. The process could become feasible if the solar concentrator price per unit were to come down.

A. The Oceans as a Potential Resource

Fresh water shortages are a major concern in many places around the world. Current sources can only be capable of providing a limited amount of water. With growing human populations, these sources are being severely taxed. People are now looking towards other possible sources for potable water. One major source could be the oceans. Consisting of approximately 97% of Earth's water, the oceans could provide all the water needed by expanding populations.²⁹ However, before seawater can be usable, it must first be desalinated. This is naturally done by evaporation due to the solar energy on the surface of the water sources such as the oceans. The evaporated water later falls back to the Earth as rain. Increasing the heat energy to the water and then capturing evaporation can accelerate this process. The problem with this is in the amount of energy required to quickly evaporate water. However, it is possible to utilize solar energy through solar concentrators to provide the energy required. Furthermore, sea salt has recently been considered a desirable commodity. After the water has been evaporated, the remaining salt can be collected and sold to help offset costs of the desalination process. This helps to resolve an issue related to dumping concentrated brine into the ocean: the ecosystems will not be affected since isolated salt is collected for sale. Furthermore, using solar concentrators provides a clean renewable energy source.⁵

B. Process Overview

The desalination process discussed in more detail below had two objectives. The first was to provide desalinated water. The second was to extract the sea salt for the added profit. A diagram of the process can be seen in Fig. 4. The steps in the process are as follows:

- Seawater was transported from the ocean to the desalination site.
- The seawater entered a heat exchanger to raise its temperature.
- The warmed seawater would then enter the boiler (powered by solar concentrators) where 95% would be evaporated.

- The evaporated steam would pass through the heat exchanger to condense back into water, while the salt and remaining water would be transported to the salt evaporation beds.
- The condensed steam would be stored until it was transported to its final location.

C. Location Selection

The ideal location for the desalination plant would be on the coast in an area with an abundance of sunlight. Several locations were considered depending on their distance from the coast and the amount of sunlight received. The main consideration for the distance was the amount of power needed to move the water. Only two aspects of the flow were considered for water transportation (the change in height and the headloss). The headloss depended on the pipe material and the flow through the pipe. The first step to calculate the headloss was to determine the Reynolds number of the flow (R_E), which can be found by equation (7)

$$R_E = \frac{\rho v D}{\mu} \quad (7)$$

where ρ is the density of the water, v the velocity of the flow, D the diameter of the pipe, and μ the dynamic viscosity of the water.

The Reynolds number along with the roughness of the pipe (assumed polyvinyl chloride (PVC)) was then used to determine the fouling factor of the pipe (f), see equation (8), where ε was the roughness of the pipe. The flow was assumed to be turbulent, since the turbulent flow was more power intensive and in most cases was indeed turbulent. The head-loss (h_1) was then determined by equation (9). The power required to move the water was dependent on the headloss and the height the water needed to be lifted to reach the site. The relation used, assuming no change in pressure and a constant flow is (10).

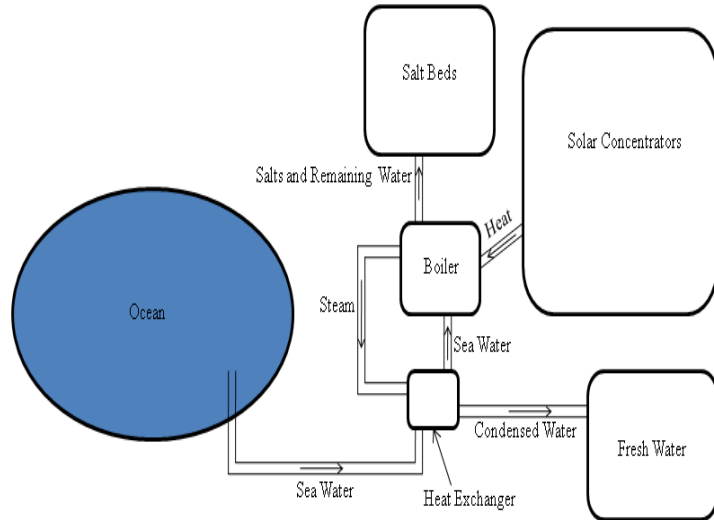


Figure 4. Solar concentrator-powered Saltwater Desalination diagram.

$$f = \sqrt{\frac{1}{-1.8 \log \left[\left(\frac{\varepsilon/D}{3.7} \right)^{1.11} + \frac{6.9}{R_E} \right]}} \quad (8)$$

$$h_1 = f \frac{L}{D} \left(\frac{v^2}{2g} \right) \quad (9)$$

$$\dot{w}_p = (z + h_1) \dot{m} g \quad (10)$$

The chosen location would therefore dictate the amount of power needed to transport the saltwater, which would depend on the distance and the height relative to the water source. The other major consideration was the amount of sunlight received. Since solar concentrators were used to provide the energy to boil the water, an area that is nearly free from clouds year round was preferable. Therefore, the best locations that were identified are found in Table 2. To compare the locations equally, the same amount of water was considered for each. Table 3 gives the initial assumptions in order to produce about 475,000 gallons per day.

Based on only the distance and elevation of the location with respect to the ocean, the best choice would appear to be the Salton Sea. However, the Salton Sea has been considered an important wetlands area and also has a limited supply of water.³² If this water source were used, it could slowly be depleted. The best location turned out to actually be Yuma, AZ. This was due primary to the cost of the solar concentrators compared to the cost of pumping the water. Since Yuma had the most sunshine, less concentrator's were needed to desalinate the same volume of water. Therefore, Yuma was selected as the location for further study.

Table 2. Locations for a Solar Concentrator Powered Water Desalination Facility

Location	Sunshine (%)	Average Number of Clear Days	Approximate Distance from Ocean (km)	Elevation (m)
Yuma, AZ	90	242	120	43
Fresno, CA	79	194	190	90
Sacramento, CA	78	188	100	8
Salton Sea, CA	~80	N/A	Inland salt lake	-69

Table 3. Assumed Pipe Flow Conditions

Variable	Value
Pipe diameter	0.6096 m
Pipe length	120000 m
Elevation of site	43 m
Velocity of water	0.2 m/s
Pump efficiency	0.5
Pipe roughness (PVC)	0.0000015 m

D. Power Requirements for Desalination

The power requirements for desalination were calculated based on the power needed to bring the saltwater to the boiling point along with the heat of evaporation of the water. The assumed values used to calculate the power requirements can be found in Table 4. Since salt would increase the boiling point of water and the concentration of salt would increase as water boils, it was assumed that the boiling temperature was 115°C. However, not all of the water was removed from the salt. The remaining water could be used to help flush out the salt. Since there was remaining water, the exiting water was a mixture of liquid and gas. The enthalpy of the mixture (h) was determined by equation (11); using the calculated enthalpy of the mixture, the thermal power required (\dot{Q}) was calculated by equation (12).

$$h = h_f + x(h_g - h_f) \quad (11)$$

$$\dot{Q} = \dot{m}c_{pw}(1 - x_s)(T_i - T_o) + \dot{m}x_sc_{ps}(T_i - T_o) + \dot{m}(h - h_f) \quad (12)$$

Table 4. Constants for Water Evaporation

Constant	Value
Water temperature (T_i)	25 °C
Temperature saturated saltwater boils (T_f)	115 °C
Composition of salt (x_s)	0.035
Percent water to steam	95 %
Enthalpy of sat liquid (h_f)	419.17 kJ/kg
Enthalpy of sat vapor (h_g)	2675.6 kJ/kg
Specific heat of water (c_{pw})	4.186 kJ/kg•K
Specific heat of salt (c_{ps})	0.854 kJ/kg•K
Dynamic viscosity at 30C (μ)	0.000798 N•s/m ²
Density of water	1000 kg/m ³
Density of salt	2160 kg/m ³

The total thermal power comes from the power required to heat the water, to heat the salt, and to evaporate the water up to the desired percentage. This power came directly from the solar concentrators. The left over saltwater mixture would be transported to a series of evaporator beds, which would allow natural evaporation to remove the remaining water.

E. Solar Concentrators

The idea behind a solar concentrator was to take a large area of solar energy and compress it to a smaller area. This directly makes use of the thermal energy available from the sun to heat the water. The thermal energy depends on a few factors such as the location and time of year. A location in the desert south of Yuma was chosen for the availability of sunlight. The location was approximately latitude 32.5° N and longitude 114.5° W. These were used with an insolation program available online to give the available insolation depending on the day, month, and year.³³ The value for each day in 2009 was used to determine the average insolation, which was used for the calculations. This means in winter less water would be desalinated and in summer more water would be desalinated. The average insolation was 331.6 W/m², and the total power needed was 146.5 MW. The solar concentrator considered was one designed and build by NASA.⁵ The concentrator was approximately 11 m² and can track the sun's movements throughout the day.

F. Estimated Costs

The unit costs to buy or sell different items can be found in Table 5. The costs were broken up into 3 categories: one time startup cost, yearly expenditures, and yearly income. A breakdown of each can be seen in Figs. 5 through 7 below. The biggest expense was in the cost of the concentrators. The estimated cost (\$5000 per concentrator) was assumed to be achievable with mass production. However, the price may need to drop further for the setup cost to be reasonable. The pump cost is the total cost of electricity needed to transport the seawater. The remaining was the assumed operation and maintenance costs.

Table 5. Estimated Unit Costs

Unit	Cost (\$/unit)	Number of Units	Total (\$)
Concentrators	5,000	52,196.6	260,983,140
Pipe (m)	34.48	120,000	4,137,931
Water (gallons)	0.0015	147,257,380	220,886.07
Sea salt (kg)	0.5	10,268,444	5,134,222
Electricity (kWh)	0.0865	331,377.6	28,664.16
Evaporator beds (m ²)	10	2,499.46	24,994.61
Land (acre)	406.25	162.86	66,162.10

It can be seen in Fig. 7 that the bulk of the income comes from the sale of sea salt due to its high selling price. This could actually cause the desalination facility to become a sea salt producing facility with fresh water being a byproduct, instead of a water facility with sea salt as a byproduct. The estimated yearly operating cost is completely covered by the income generated from selling the water (operating expense = \$107,328 and water income = \$220,886). This would leave the entire sale of sea salt as profit year to year. However, this profit must first go towards covering the startup costs. Assuming an extremely low interest rate of 1% yearly, it would still take 30 years to pay off the initial debt, which leaves no room for expansion or replacement of worn out concentrators for that 30 year period.

G. Pipe Flow

There were two costs associated with transporting seawater. One was the reoccurring pumping costs, and the other was the cost of the actual pipe. The piping used was PVC, since any metal pipe would have heavy corrosion problems due to the saltwater. In order to allow for expansion and to reduce pumping costs, a large diameter (0.6096 m) pipe was chosen. However, this pipe may not be large enough to carry the 128 million gallons per day that some of the larger desalination plants process.³⁴ To produce 128 million gallons per day of fresh water would require over \$2 billion in electricity per day just to pump in the water. This is obviously impractical, but the

optimum point has yet to be calculated. To reach a production rate of 128 million gallons per day would therefore require multiple pipelines to be within reasonable limits.

H. Case for Solar Concentrator Technology to Produce Clean Water

A water desalination facility powered by solar concentrators would be able to fund itself during operation, assuming public financing covered costs for the plant. However, unless the capital equipment costs of solar concentrators decrease, the facility would not be able to recoup the initial startup cost. Nevertheless, the system would still save money in the long run. Using the average cost of electricity in Arizona (0.0865 \$/kWh), the total cost of the solar concentrators would equal about 6.6 years worth of electricity running off the power grid for the same amount of power (not accounting for losses in converting electrical power to thermal). Furthermore, this process makes use of a clean renewable resource (the sun) to provide needed freshwater.

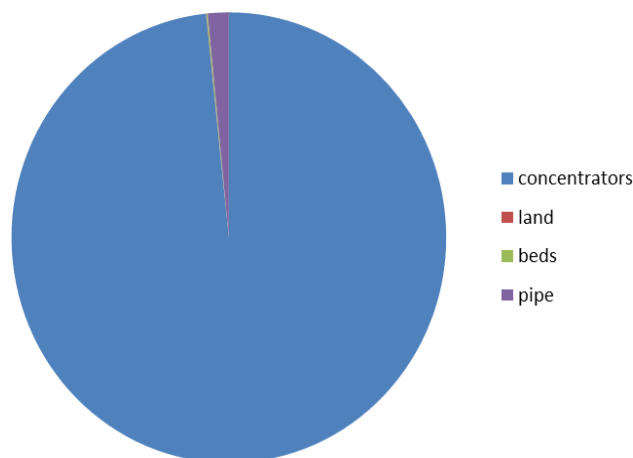


Figure 5. Breakdown of startup expenses.

IV. Resource Utilization on the Moon

Oxygen is the highest-value resource to be produced on extraterrestrial bodies such as the moon,^{1,2} since it is the oxidizer component of rocket propellant, and is, for most chemical rocket types, the most massive component of the fuel used for propulsion. Thus, production of oxygen from local material fuels the transportation system that supports the lunar base, as well as serving as a possible product for use in propulsion systems either commercially or to support exploration of other locations. Replacement oxygen is also a necessary product for life support, since even closed-ecological life support systems will not have perfect efficiency of recycling.

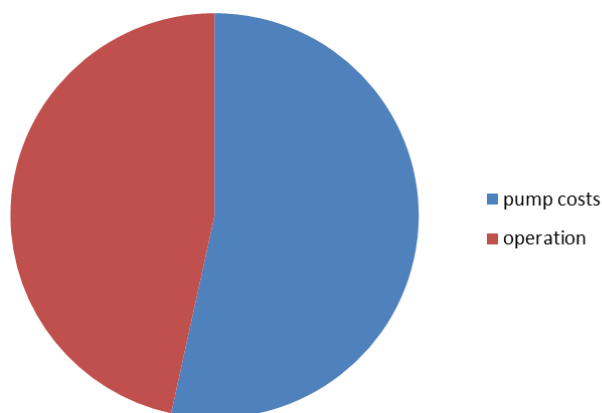


Figure 6. Breakdown of yearly operating costs.

In addition to the oxidizer, it would be desirable to produce the fuel as well. This is more difficult to produce from lunar material, since hydrocarbons are absent. The polar regions of the moon are now understood to have permanently shadowed craters, in which water ice is present; this ice could be mined and then electrolyzed to produce hydrogen and oxygen, which can be used for fuel, although liquid hydrogen is difficult to store, requiring cryogenic tankage. The high latitudes of the moon also contain water in the form of hydrated minerals. An alternate technology would be to develop rockets that do not utilize hydrogen or hydrocarbons. One alternative is metal propellants, such as aluminum (Al) or magnesium (Mg).³

However, it will also be desirable to refine raw materials for other purposes, including structural materials and materials for industrial applications, such as production of solar arrays.³⁵ Many possible applications for lunar-produced materials are summarized by Benaroya.³⁶ The most desirable processing sequence therefore would focus on an initial goal of oxygen production, but using a

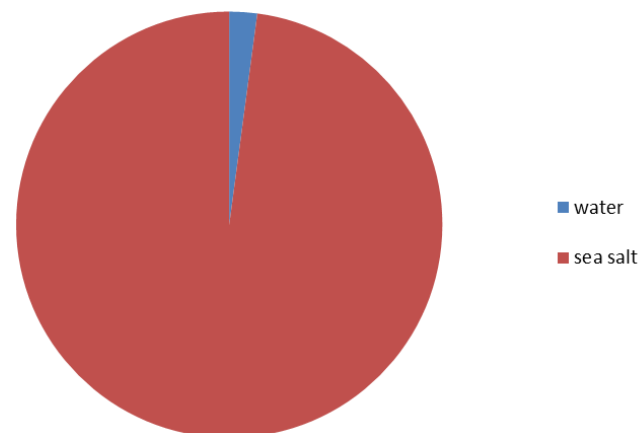


Figure 7. Breakdown of yearly income.

technique that could be expanded to produce and refine other raw materials.

Technologies for refining raw materials out of lunar rock will also have applications on Earth. Terrestrial refining technologies used today require significant use of resources such as coal, energy, and water, and produce large amounts of waste byproduct such as carbon dioxide and particulate pollution. Lunar resource extraction, on the other hand, must of necessity minimize the use of expendable resources, will recycle reactants and exhaust gasses, and will be optimized to be efficient in the use of energy. Thus, pilot production sequences for lunar resource utilization will serve as models for highly efficient, not-polluting technologies that can be made on Earth.

Work at GRC has examined several methods of materials production from lunar regolith.^{3,35,37,38} The same process sequences could be used at other locations. Stony asteroids typically have regolith similar to that of the moon, and refining of asteroidal material could use the same techniques, adapted for microgravity. Other types of asteroids would allow processing possibilities not considered here. For example, Type-C asteroids contain carbon and can contain some amount of chemically bound water, which can be used for different purposes. Metallic asteroids can be processed to produce both bulk and precious metals. Likewise, Martian rock and soil could also be processed by the techniques discussed here.

A. Desirable Products from Lunar Regolith

Other than oxygen, metals, glass and related ceramics and silicon are valuable as structural and power materials. Each sub-section gives examples of practical applications of these materials for an eventual lunar colony.

1. Metals

Metals are a ubiquitous structural material, and will certainly be used in lunar manufacturing. Structural metals include iron and steel, aluminum, and titanium; each valuable for different uses, and all available as elemental components of lunar material. Metals are also used as wires conductors. From its elemental abundance in lunar soil and high electrical conductivity, aluminum is the clear choice for wires. A second possible choice is calcium, not used on Earth because of high reactivity with oxygen, but a possible conductor for vacuum applications.

2. Glass and ceramics

Transparent glass is a required material in forming solar arrays.³⁵ Ceramics are also useful as insulators. Glass or ceramic fibers are useful for structural composites. The primary glass-forming material, silicon oxide, is abundant on the moon, in the form of silicates. Transparency requires refining, most particularly to remove trace amounts of iron and other transition-metal oxides, which produce color centers. Usable glass is not merely silicon oxide, but an engineered material with many components selected to produce the required properties. Several of the oxides which are used to adjust the properties of glass are not abundant on the moon. Sodium oxide (Na_2O), the main component of “soda lime glass,” is typically used to reduce the melting point, allowing easier working. Boron oxide (B_2O_3), to produce borosilicate glass, is typically used to adjust the thermal expansion coefficient. New glass compositions will have to be invented to reduce, or eliminate, the amounts of these materials that are rare in lunar soil.

3. Silicon

One of the most important issues for settlement is production of power. Many different semiconductors can be used to produce photovoltaic cells, but from the standpoint of lunar abundance of materials, the clear choice for locally-manufactured cells is silicon solar cells.⁵⁵ Silicon suitable for semiconductor applications is a highly purified product; parts per billion of some impurities is sufficient to degrade the properties. Thus, a processing sequence for making solar-cell grade silicon must include purification steps.

4. Civil-engineering materials

In addition to structural materials, lunar settlements will undoubtedly require less highly processed material. Although habitation structures on the moon will not be made of ordinary bricks (since habitats must hold pressure, and hence will be tension structures), there will still be the need for the equivalent of concrete, asphalt, and bricks. Many possibilities for such bulk material exist, including sintered or melted regolith bricks, material produced from slag from other processes, or composite materials comprising aggregate fill cemented with a ceramic matrix.

B. Processing Methods

A processing sequence can be broken into three main steps: (1) Acquisition and beneficiation (if required) of feedstock; (2) Reduction; and (3) Refining of the desired raw materials and purification to the required level. What follows is a brief overview followed by a focus primarily on three different approaches to the second step, reduction.

1. Processing Overview

The acquisition portion of the processing is a sequence of prospecting (if required), materials acquisition and mining, grinding or otherwise preparing the material for processing, and (for some sequences) beneficiation of the input material to increase the concentration of the desired mineral. Preferably, the sequence selected could be fed from regolith that is available at any lunar location, minimizing and possibly eliminating the need for prospecting and for beneficiation.

The reduction step comprises stripping the oxygen away from oxides. This step produces the main product, oxygen. Lunar regolith is primarily silicates, in which the oxides are in the form of oxygen bridging between silicon atoms, chemically bonded to metal cations in a strongly-bound net. The reduction process therefore requires breaking the silicon-oxygen bonds.

After the oxygen is produced, the byproduct is reduced (or partially-reduced) metals. The resultant product may be a mixture of metals. To turn this into useable raw material, the desired materials must be separated and purified to the levels needed. Many sequences for oxygen production have been previously reviewed.¹⁻³ Sequences of interest here are those that reduce the main components of lunar regolith, to produce metals.

2. Magma Electrolysis

Magma electrolysis is conceptually the simplest method of refining regolith into reduced metals and oxygen. It consists of heating lunar soil to the melting point, then running electrical current through the melt to electrolyze the anions (primarily oxygen) at one electrode, and the cations (metals and Si) at the other.³⁶ However, the details are complicated. A significant difficulty is the extremely high temperatures needed, from 1300 °C to 1450 °C, which result in significant practical difficulties.

3. Calcium Process

A two-step calcium process is feasible as a method of reducing temperatures needed.³⁷ It requires considerably lower temperatures than direct magma electrolysis, and produces oxygen with considerably higher efficiency than hydrogen or carbothermal reduction methods. The first step consists of reducing the regolith by calciothermic reduction. This is done by heating of regolith in the presence of metallic calcium, to convert the silicates into metals plus calcium oxide. Regolith is heated with metallic calcium at a temperature greater than the melting point of calcium, 845°C. The reaction rate is increased by use of finely-ground reactants as well as excess calcium; equation (13) shows a typical reaction:



The second step (14) regenerates the metallic reactant, by electrolyzing the calcium oxide in a molten salt at 825-900 °C, to produce metallic calcium and oxygen:

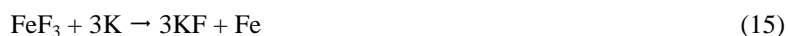


Since calcium and calcium oxide are soluble in calcium chloride (CaCl₂), the chloride or a CaO/CaCl₂ eutectic mix can be used as a flux to accomplish the reactions in a liquid solution. Further separation and purification steps can be taken from this point to produce refined product for other processing.

4. Fluorine Process

The basic reduction process is to heat the regolith in the presence of fluorine. The fluorine displaces the oxygen from the rock (collected as a useful product), producing fluorides. The fluorides are displaced by potassium to produce reduced metals and potassium fluoride (KF), which is electrolyzed.^{35,38}

Silicon and titanium produce volatile fluorides, SiF₄ and TiF₄, both gaseous at the processing temperature. The tetrafluorosilane can be easily purified to semiconductor-grade by distillation. The remaining metals are produced in the form of fluoride salts, which must be reduced to the metals. The iron and aluminum fluorine salts are directly reduced with potassium:



Calcium and magnesium fluorides are not reduced by potassium, and are returned to oxide form by potassium substitution:



The oxides are then available for glassmaking. The reactants, fluorine and potassium, are returned in the form of KF, and are then recovered by electrolysis in a KF/NaF/CaF₂ eutectic at 676 °C.

C. Impact of Geographical Location

On the lunar surface there are two main types of soils available. These consist of the older, brighter soils at high topographies, termed highlands, and the darker basaltic lava flows of the mare located at lower topographies.⁴ A display of the topography on the moon is shown in Fig. 8.³⁹ The regolith at the highlands and Mare have different compositions and therefore different oxygen production processes are applicable to each of these areas. The hydrogen reduction process for producing oxygen can

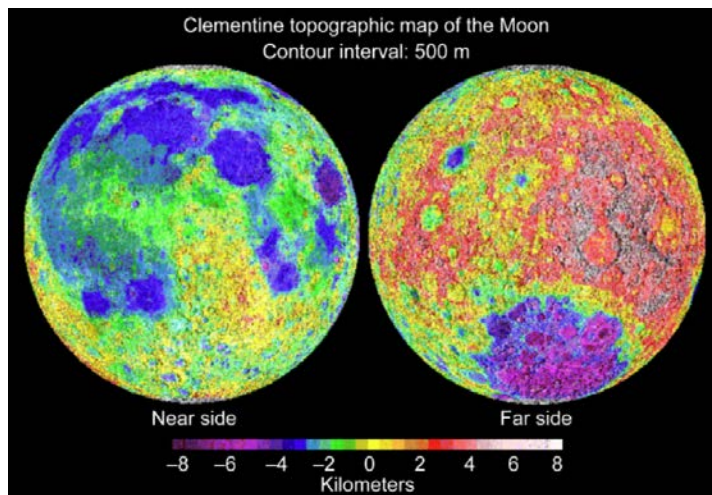


Figure 8. Topographic map of the Moon determined by the Clementine mission of 1999.

yield 1% to 5% of oxygen per unit volume of ilmenite.²⁴ For comparison the carbothermal oxygen production process requires high enough temperatures to melt the regolith (~1800 K), but can be used with most of the metal oxide compounds found in the regolith. The oxygen yield of the process is approximately 15% by weight.⁴

For locations within the mare regions, either hydrogen reduction or carbothermal reduction can be used as an oxygen production process. Since ilmenite is not found in usable amounts in the highland regions,⁴⁰ the carbothermal process would be utilized within these regions. This means higher temperatures and more precise concentrator optics are required.

Though both the mare and the highlands have different regolith characteristics, they both have one significant problem; for approximately 14 Earth days, most of the mare and highland topographies are enshrouded in darkness.⁴¹ Because the Moon's axis is angled 1.5 degrees from the ecliptic, the South pole is almost constantly bathed in sunlight; during lunar summer, the entire South Pole is visible, and during lunar winter, the Shackleton crater and other small southern regions are illuminated by the Sun for more than 70% of the time.⁴¹

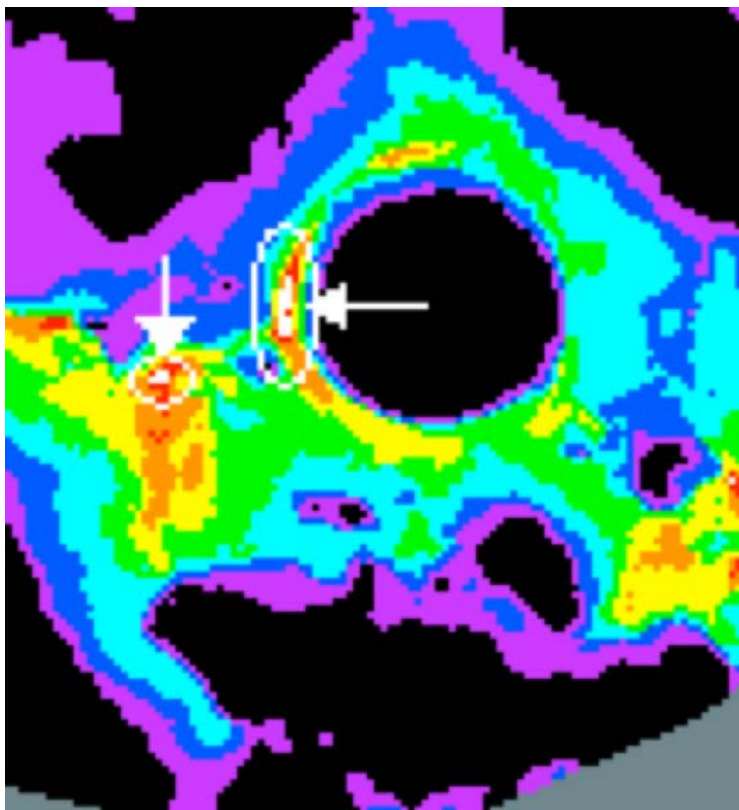


Figure 9. Percentage of time with solar illumination during lunar winter. The arrows are pointing at the two regions that are illuminated >70% of the time during lunar winter; near the Shackleton Rim.

Figure 9 shows the percentage of time regions near the South Pole geographies are illuminated during lunar winter. Such areas would be an ideal place for a constantly operating solar concentrator that could generate approximately twice the amount of oxygen than an ISRU system anywhere else on the moon. However, there are minimal deposits of iron and titanium located at the poles.⁴⁰ Less than 1% of ilmenite is present which means hydrogen reduction would not be the preferred oxygen production method; carbothermal reduction or other non-mineral-specific processes must be pursued.

V. Beyond the Moon: Future Human Exploration Options

In the 1950's, 1960's, 1970's, and 1980's, ambitious robotic and human missions were planned, spanning from Mercury to the outermost reaches of the solar system.⁴²⁻⁴⁶ While investments in robotic missions have continued, human exploration of the solar system has awaited new invigorating steps. Beyond the moon, Mars represents an obvious destination for human exploration, and also a rich destination for use of in-situ resources. Mars resource utilization is incorporated into reference plans for exploration of Mars.⁴⁷ The literature on Mars resource extraction and utilization is sufficiently extensive that it will not be covered in this paper. Future human missions to other destinations such as Mercury and Saturn will also require long-term investments. Currently, Mercury and Saturn have robotic missions returning invaluable data on those planets and their environs. These data have provided insights that will ensure the success of future missions. With its proximity to the Sun, Mercury has extremely high temperatures and requires special high heat flux considerations for long-term human visits or bases. In contrast, temperatures at Saturn and its moons require designs for cryogenic environments. The possibilities for in-situ resource utilization (ISRU) may allow more effective robotic missions and human visits to these planetary targets.

A. Mercury

Mercury is the closest planet to the Sun; ranging from a perihelion of 46 million km to an aphelion of nearly 70 million km. The high temperature, high heat flux environment at Mercury and the tenuous surface emanations of several major chemical species (sodium, etc.) surrounding it will likely pose challenges to long term human visits. Permanently shadowed craters offer a valuable niche for longer-term human visits and planetary bases. Such craters offer cryogenic temperatures while the sun-facing surface is at a temperature of 590 to 725 degrees K. The north polar regions of Mercury have been identified as a likely location for such permanently shadowed craters.⁴⁸⁻⁵⁰ Water ice is also likely to be in these craters, further aiding and assisting any human exploration(s). Short exploratory missions can be accomplished with hopping ascent-descent vehicles from the base at the shadowed crater.

Figure 10 shows the locations of the shadowed craters.⁴⁹ Figure 11 depicts the temperatures that would exist in and near the craters.⁵⁰ The crater could accommodate a small base

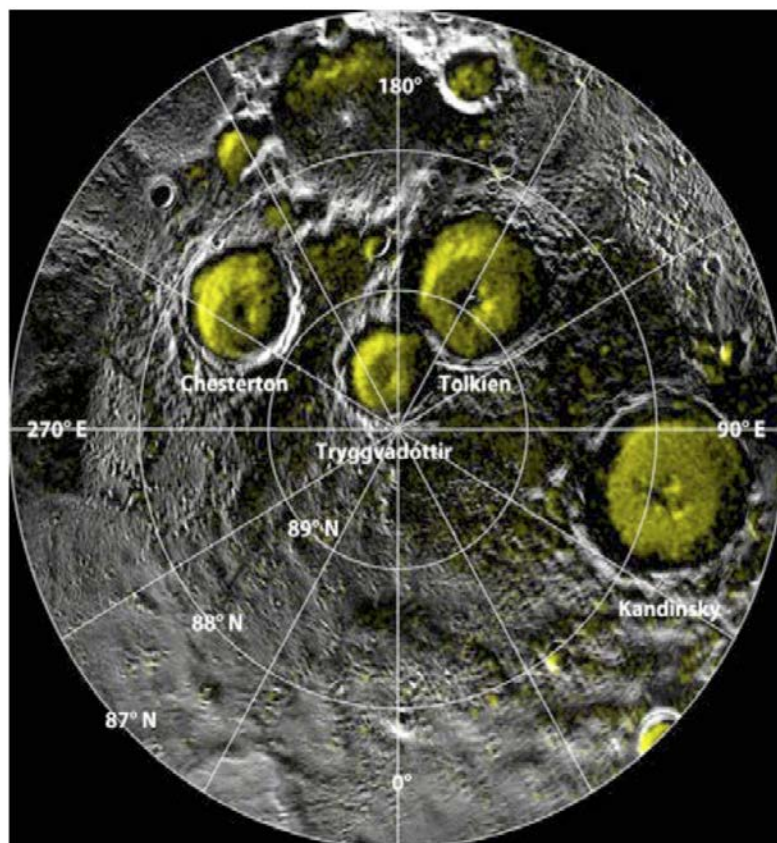


Figure 10. Permanently shadowed craters in Mercury's north polar region (from Ref. 49).

or at least an initial landing site. The lander's temperature could stay within the nominal operating temperatures of traditional spacecraft. The temperature distribution in the crater would allow construction of the base at the warmer side of the crater and then the frozen volatiles would be extracted with cryogenic mining machines.

B. Mercury Missions

A human round trip mission to Mercury was assessed. The mission ΔV values for the round trip Mercury missions were derived from the literature.⁵¹⁻⁵⁴ The highest ΔV case was selected from this data: an Earth departure delta-V of 5.2 km/s, a Mercury arrival ΔV of 10.9 km/s and a Mercury departure ΔV of 8.7 km/s.⁵¹ At Earth a capsule enters the atmosphere to return the crew directly to Earth. The capsule's mass is 4,350 kg; the round trip time is 585 days with a 40-day stay time at Mercury.⁵¹ In this case, the vehicle does not land on Mercury. The LEO masses of both chemical propulsion and nuclear thermal propulsion vehicles were estimated. Figure 12 compares the LEO masses for 2 types of chemical propulsion systems and 2 nuclear thermal propulsion (NTP) systems. The interplanetary chemical propulsion systems used tankage dry mass coefficients of 3% and 5% of the total propellant mass in the tankage. In many cases, these dry masses may be deemed to be optimistically low; however, they allow some relative comparison of the chemical propulsion and the nuclear mission cases.

The NTP vehicles dry mass was 15% of the propellant mass. In current NTP designs, an I_{sp} of 900 seconds is nominally used.^{55,56} Somewhat lower I_{sp} values were used for these missions: 800 and 850 seconds, respectively. These lower I_{sp} values were assumed given the high heat flux environment of Mercury and the degraded I_{sp} values would reflect the added propellant used for propellant cooling and/or refrigeration. The chemical propulsion systems required between 17,150 MT and 31,230 MT to accomplish the mission. The NTP vehicles required approximately an order of magnitude less mass in LEO: 1,700 MT to 2,300 MT. Based on our prior analysis, the stage and lander mass was estimated with a mass scaling equation (19).⁵⁷

$$M_{dry,stage} (kg) = M_{dry,coefficient} \cdot M_p (kg) \quad (19)$$

A Mercury landing vehicle mass was also estimated; the one-way ΔV for the lander was 3.5 km/s.⁵⁸ The ascent ΔV was also 3.5 km/s. These ΔV values accommodate approximately 19% for gravity losses for each maneuver; this gravity loss ΔV is added to the orbital velocity for a 100 km orbit which is 2.945 km/s. The lander I_{sp} was 480 seconds. The higher I_{sp} was chosen for the lander as the engine used a higher engine expansion ratio than the interplanetary transfer vehicle.⁵⁷ The smaller engine size would allow a higher expansion ratio, given the typical volume constraints for space vehicles. The dry mass coefficient was 20% of the total propellant load. While the Mercury missions will likely require more aggressive thermal control (propellant shielding, cooling, etc.), that thermal control system mass is accommodated in the payload mass of the vehicle. The payload delivered to the surface was 10 MT. Figure 13 compares the mass in LEO of a one-way lander and a round trip lander. The masses

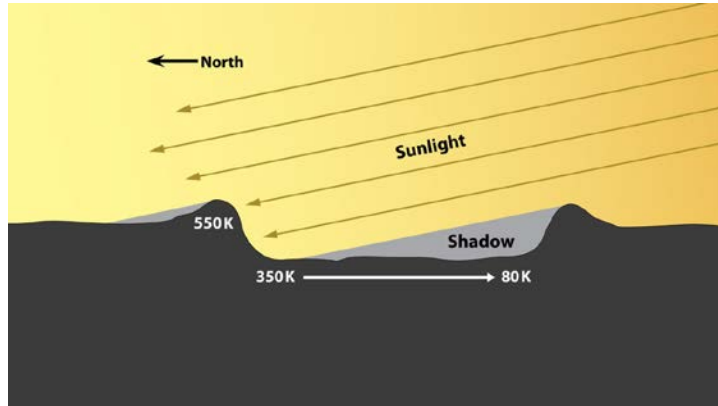


Figure 11. Temperature ranges outside and inside permanently shadowed craters (from Ref. 50).

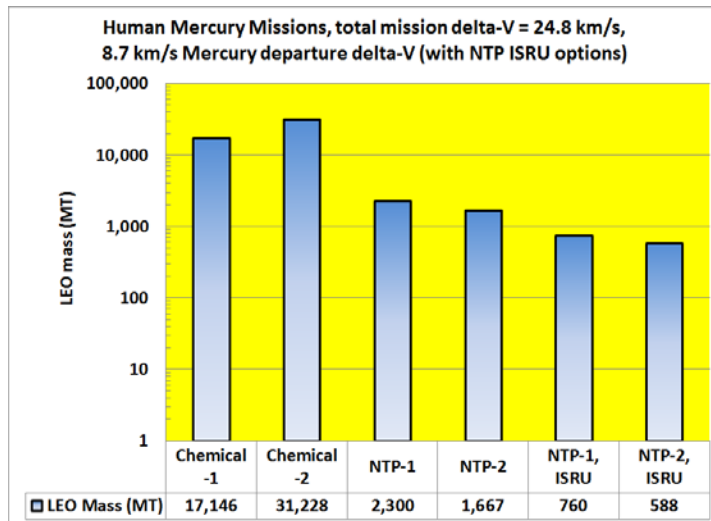


Figure 12. LEO masses of human round trip missions to Mercury.

were 140 MT for the round trip lander and 27 MT for the one-way lander. Thus, using ISRU on the surface of Mercury to replenish the lander's propellant would allow a savings of 113 MT on this mission. Additional analyses are needed to investigate the mass reductions for the interplanetary transfer vehicle to carry the lander to Mercury. Another option would be to carry 5 landers to Mercury rather than carry simply one lander; many more permanently shadowed craters could then be visited on one mission. The interplanetary vehicle carrying the 5 landers could be sent on a lower energy trajectory than the human flights, thus saving additional mass launched into LEO in the overall Mercury architecture.

Table 6. Space Vehicle Dry Mass Coefficient and Rocket Engine Specific Impulse (I_{sp})

Technology	I_{sp} (sec)	$M_{dry,coefficient}$ (kg/kg M,p)
Chemical-1	450	0.03
Chemical-2	450	0.05
Chemical lander	450	0.20
NTP-1	800	0.15
NTP-2	850	0.15

Using Mercury resources to augment the human missions was investigated. An ISRU system's effect on reducing the LEO mass (see Table 6 for details) was analyzed. For the NTP-1 and -2 systems, cases were computed where the Mercury departure ΔV propellant was supplied at Mercury. The Mercury departure stage is brought from Earth with no propellant. Hydrogen would be produced from the water at the northern polar craters, and transported to orbit. For the NTP-1 case, 94 MT of hydrogen would be transported to orbit. With NTP-2, the propellant mass required in Mercury orbit is 82 MT. With the in-situ hydrogen production, the LEO mass of the NTP-1 case is reduced from 2300 MT to 760 MT, as shown in Figure 12. Similar large LEO mass reductions are enabled for the NTP-2 system; using ISRU, the 1667 MT LEO mass is reduced to 588 MT.

Additional summary data on mission design is summarized in a review. Figure 14 provides a map of the one-way ΔV and trip time for a wide range of planetary targets.⁵⁴ Fast missions to Jupiter and Mercury are possible with ΔV values of 80 to 100 km/s. Nuclear propulsion systems may someday allow such ambitious missions and if augmented by ISRU, such mission will be within our technological reach.

C. Venus

The next planet out from the sun, Venus, is one of the most hostile surface environments in the solar system, with a surface temperature of 450°C at an atmospheric pressure of 92 bars. Nevertheless, Venus, as a rocky planet with a thick atmosphere, is the planet in the solar system that is in many ways most similar to the Earth, and hence scientific study of Venus is of significant interest. The atmosphere, consisting primarily of carbon dioxide and nitrogen, with clouds of sulfuric acid, represents a resource that may be of interest in long-term human settlement.

As with Earth, the temperature in the atmosphere decreases due to adiabatic lapse as the altitude increases, and at an altitude of about 56 km above the surface, the temperature reaches Earthlike values

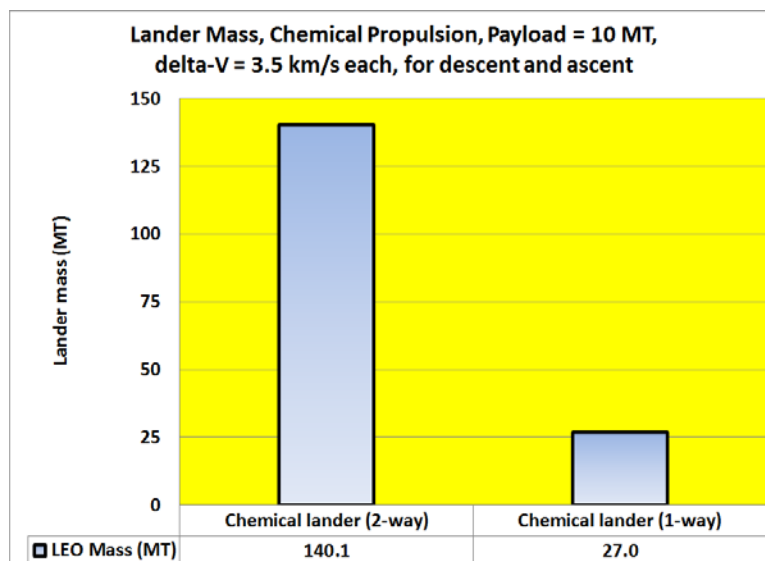


Figure 13. LEO masses of landers for missions to Mercury.

of about 20°C, at a pressure of about half a bar. If human habitats were to be emplaced at Venus, this altitude would be an Earthlike location.⁵⁹

Terraforming, the process of altering a planetary environment to make it hospitable to life, has been proposed for both Venus and Mars.⁶⁰ Terraforming Venus is a process which would require long periods of time and large expenditures of energy, but which may not be beyond the reach of future engineering capabilities.⁶¹

D. Jupiter and its Moons

Jupiter, the largest planet in the solar system, is a challenging target for exploration. Because of the high gravity and deep gravitational well, Jupiter itself is probably beyond the reach of human exploration, but the extensive system of Jovian moons, including the four large Galilean moons and a number of smaller moons. The innermost moon, Io, has a volcanic, sulfur-rich surface; Europa shows an icy surface, while Callisto and Ganymede show evidence of regolith on the surface covering ice. Europa and Ganymede, and very likely also Callisto, also shows evidence of a subsurface ocean. Of these, only Callisto lies outside the Jovian radiation belts, and hence is a reasonable target for human exploration.⁶²

Beyond the large Galilean moons, the smaller moons of Jupiter are asteroid-like bodies, which very likely are partly or mostly ice in composition. The Trojan asteroids, leading and trailing Jupiter's orbit around the sun, also represent sources of ice. Thus, the moons of Jupiter may well be a source of volatile elements, primarily water, which may represent useful resources for production of fuel and life-support consumables.

E. Saturn and its Moons

Saturn is one of the outer planets. Its orbit has a perihelion of 1,352.6 million km and an aphelion of 1,514.50 million km. The Cassini spacecraft has conducted an extensive series of flybys of the Saturnian moons. During these flybys, cameras and instruments capture and data on the moons' composition, atmosphere and cloud cover (on the moon Titan), volcanoes, plumes, rotation, and gravity.

Titan is the largest moon of Saturn. It is the second largest moon in the solar system, the only moon with an atmosphere, and the only body in the solar system (other than Earth) that shows bodies of liquid on its surface. It is thus one of the most scientifically interesting targets for exploration in the solar system. Its intriguing nature includes a nitrogen and methane atmosphere and a subsurface ocean, as shown in Figure 15.⁶³ Recent flybys of the Cassini spacecraft have shown direct visual evidence of the northern lakes which are likely composed of methane. Based on measurements and theories of the evolution of Titan, a large ocean of water and ammonia may exist below the icy surface. Large lakes in the northern polar regions have been seen on Titan's surface, and they are likely composed of liquid methane. Figure 15 shows the possible nature of Titan's interior, surface, and atmosphere. While methane can be used as an effective rocket propellant, its nitrogen could be used in cold gas propulsion or electric propulsion (resistojet, arcjet or magneto-plasma-dynamic (MPD) thrusters).

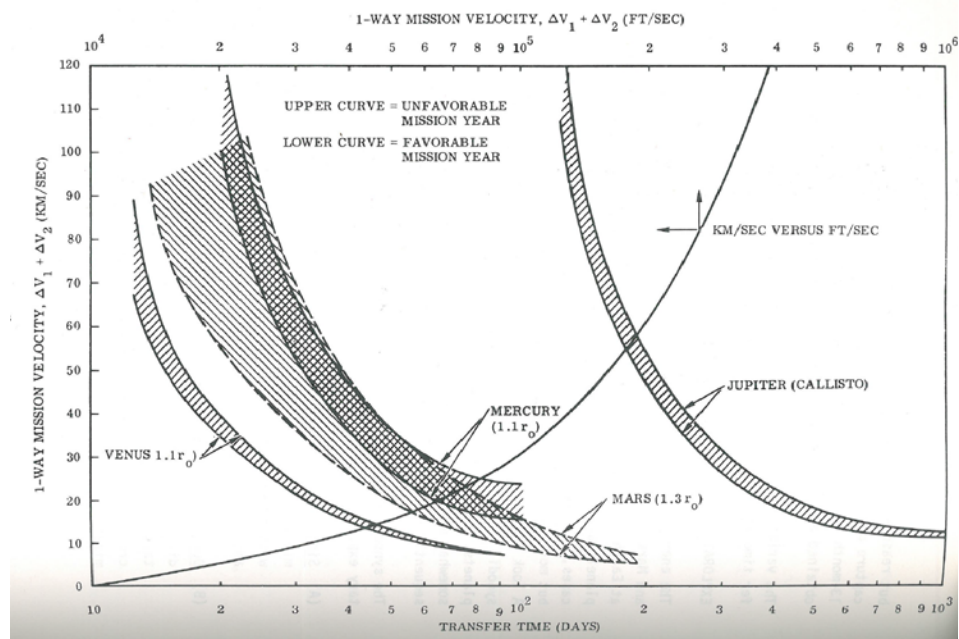


Figure 14. One-way interplanetary mission ΔV versus trip time for various targets (from Ref. 54).

F. Atmospheric Mining in the Outer Solar System

Atmospheric mining in the outer solar system (AMOSS) can be a powerful ISRU tool in extracting fuels from the outer planets and allow fast human and robotic exploration of the solar system. Preliminary designs of aerospacecraft with gas core rocket nuclear engines for mining the outer planets were developed.^{55,56} Helium-3 (^3He), a possible fuel for advanced nuclear fusion reactor cycles based on the D- ^3He reaction, would be extracted from the atmosphere and stored for final delivery to orbital assets.

The outer planets Uranus and Neptune are the most reasonable targets for such atmospheric extraction of ^3He , since their atmospheres, although primarily hydrogen, contain significant amounts of helium, and the gravitational potential is much less steep than that of Jupiter or Saturn.

Analyses showed that gas core nuclear rocket (GCNR) engines can reduce the mass of such aerospacecraft mining vehicles very significantly: from 72 to 80 percent reduction over nuclear thermal propulsion (NTP) solid core powered aerospacecraft mining vehicles. While this mass reduction is important in reducing the mass of the overall mining system, the complexity of a fissioning plasma gas core rocket is much higher than the more traditional solid-core NTP engines.

Additional analyses were conducted to calculate the capture rates of ^3He , hydrogen and ^4He during the mining process. Very large masses of hydrogen and ^4He are produced every day during the often-lengthy process (multi-day) of ^3He capture and gas separation.

Figure 16 shows the mass of hydrogen needed for the gas core rocket and the potentially excess hydrogen captured every day.⁵⁶

Typically, these very large additional fuel masses can dwarf the requirements needed for hydrogen captured for ascent to orbit. Thus, the potential for fueling small and large fleets of additional exploration and exploitation vehicles exists. Aerial vehicle designs can take on many configurations. Additional aerospacecraft or other uninhabited aerial vehicles, or balloons, rockets, etc., could

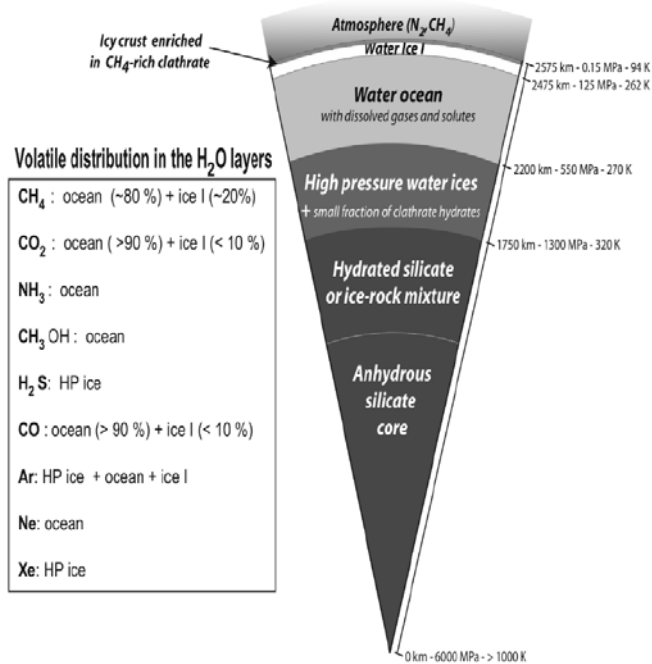


Figure 15. Possible present day cross-section of Titan (from Ref. 63).

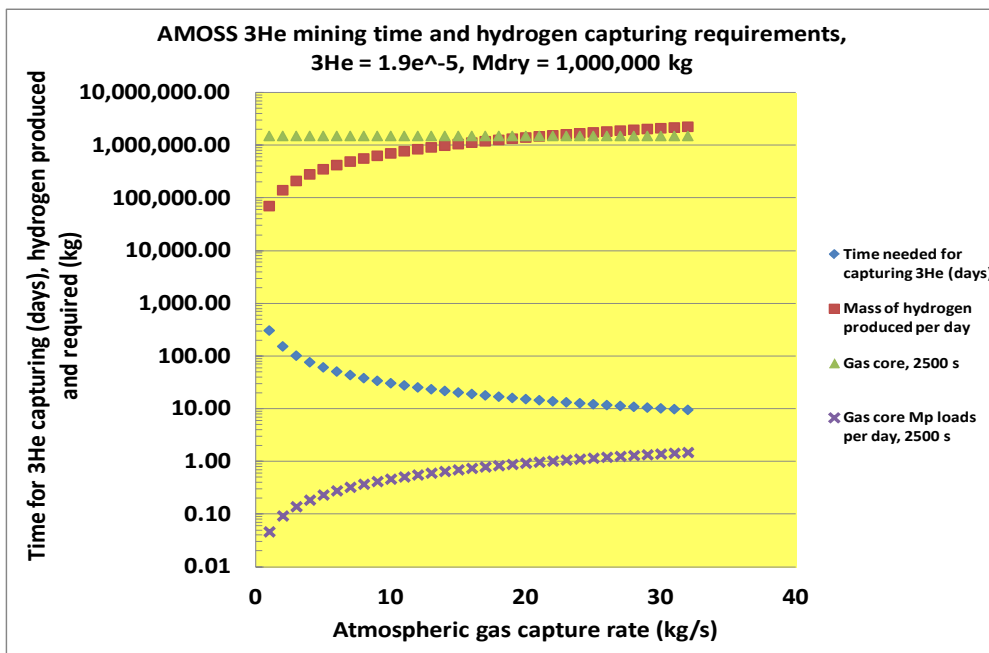


Figure 16. Helium Helium-3 mining time and hydrogen capture (mass per day) versus atmospheric gas capture rate for Neptune AMOSS.

fly through the outer planet atmospheres, for global weather observations, localized storm or other disturbance investigations, wind speed measurements, polar observations, etc. Deep-diving aircraft (built with the strength to withstand many atmospheres of pressure) powered by the excess hydrogen or ^4He may be designed to probe the higher density regions of the gas giants.

Based on these past analyses, there will likely be several possible future avenues for effective use the gases of the outer planets for exciting and scientifically important atmospheric exploration missions. The analyses focused on Uranus and Neptune, as these planets offer vast reservoirs of fuels that are more readily accessible than those from Jupiter and Saturn (as these latter planets require lower energies needed to attain orbit and present less danger from powerful atmospheric lightning) and, with the advent of nuclear fusion propulsion, may offer us the best option for fast interplanetary travel and the first practical interstellar flight.

VI. Conclusions

As amply demonstrated in this retrospective analysis, “Living off the land” imposes severe constraints for utilization of power, propellants, and other expendables. The normal rigors (mass, space limitations and environmental challenges) imposed by space travel are magnified by a resource-limited situation. On the other hand, enhanced energy efficiency and minimal launch mass will simplify missions (and increase successful outcomes) by resultant limitations to planned activities. Thus the technical hurdles and challenges alluded to above will stimulate development of technology solutions for space exploration that can be spun off to solve terrestrial problems for defense, dual-use, and commercial transportation, power generation, and efficient resource utilization. Another important aspect of the NASA GRC effort that should certainly not be overlooked is the variety of individual collaborations fostered, organizational partnerships formed, and students educated and brought into the aerospace community as a result of the technical work.

In-flight utilization of waste and trash to produce essential materials such as water, fuel(s), and oxygen is an anthropogenic-waste application of an ISRU approach for sustainability. For prudent and efficient utilization of terrestrial raw materials and energy for transportation fuel production, re-use or recovery of hydrocarbons and waste is becoming increasingly critical in overall system designs. In an effort to provide fresh water through desalination in a clean, economical, and environmentally friendly way, a solar powered water desalination facility located in Yuma, AZ was considered. Such a facility powered by solar concentrators would be able to fund itself during operation, assuming public financing covered costs for the plant; unless the capital equipment costs of solar concentrators decrease, the facility would not be able to recoup the initial startup cost. Nevertheless, the system would still save money in the long run.

Production of oxygen from local material can fuel a transportation system that supports the lunar base, as well as serving as a possible product for use in propulsion systems either commercially or to support exploration of other locations. Replacement oxygen is also a necessary product for life support, since even closed-ecological life support systems will not have perfect efficiency of recycling. Because the Moon’s axis is angled 1.5 degrees from the ecliptic, the South pole is almost constantly bathed in sunlight; during lunar summer, the entire South Pole is visible, and during lunar winter, the Shackleton crater and other small southern regions are illuminated by the Sun for more than 70% of the time. Such areas would be an ideal place for a constantly operating solar concentrator that could generate approximately twice the amount of oxygen than an ISRU system anywhere else on the moon.

Fast missions to Jupiter and Mercury are possible with ΔV values of 80 to 100 km/s. Nuclear propulsion systems may someday allow such ambitious missions and if augmented by ISRU, such mission will be within our technological reach. With its proximity to the Sun, Mercury has extremely high temperatures and requires special high heat flux considerations for long-term human visits or bases. There will likely be several possible future avenues for effective use the gases of the outer planets for exciting and scientifically important atmospheric exploration missions. The analyses focused on Uranus and Neptune, as these planets offer vast reservoirs of fuels that are relatively readily accessible; with the advent of nuclear fusion propulsion, these most distant gas giants may offer us the best option for fast interplanetary travel and the first practical interstellar flight.

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