NASA
In-Situ Resource Utilization (ISRU) Capability Roadmap
Final Report

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Chair: Gerald B. Sanders, NASA/JSC
Co-Chair: Dr. Michael Duke, Colorado School of Mines

Primary Team Members

NASA
Diane Linne, GRC
Kurt Sacksteder, GRC
Stu Nozette, HQ
Don Rapp, JPL
Mike Downey, JSC
David McKay, JSC
Kris Romig, JSC
Robert Johnson, KSC
William Larson, KSC
Peter Curreri, MSFC

Industry
Ed McCullough, Boeing
Eric Rice, Orbitec
Larry Clark, Lockheed Martin
Robert Zubrin, Pioneer Astronautics

Academia
Brad Blair, Colorado School of Mines
Leslie Gertsch, University of Missouri-Rolla

Critical Volunteers
Dale Boucher, NORCAT
Trygve “Spike” Magelssen, Futron
Alex Ignatiev, Univ. of Houston
Darryl Calkins/Army Cold Regions Research & Eng. Lab
Klaus P. Heiss, High Frontier
Tom Simon, JSC
Ron Schlagheck, Laurent Sibille, Ray French, Julie Ray, & Mark Nall, MSFC
- Further list of volunteers for each ISRU Element team

Coordinators
Directorate: John Mankins, ESMD
APIO/JPL: Rob Mueller, Affiliation

Description of ISRU Capability

The purpose of In-Situ Resource Utilization (ISRU), or "living off the land", is to harness and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. ISRU can be the key to implementing a sustained and affordable human and robotic program to explore the solar system and beyond. Potential space resources include water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.)[1], vast quantities of metals and minerals, atmospheric constituents, abundant solar energy, regions of permanent light and darkness, the vacuum and zero-gravity of space itself, and even trash and waste from human crew activities. Suitable processing can transform these raw resources into useful materials and products.

Today, missions must bring all of the propellant, air, food, water and habitable volumes and shielding needed to sustain the crew for trips beyond Earth. Resources for propellants, life support, and construction of support systems and habitats must be found in space and utilized if humans ever hope to explore and colonize space beyond Earth. The immediate goal of ISRU is to greatly reduce the direct expense of humans going to and returning from the Moon and Mars, and then to build toward self-sufficiency of long-duration manned space bases to expand our exploration efforts and possibly to return energy or valuable resources to Earth. Four major areas of ISRU that have been shown to have great benefit to future robotic and human exploration architectures are:

- Mission consumable production (propellants, fuel cell reagents, life support consumables, and feedstock for manufacturing & construction)
- Surface construction (radiation shields, landing pads, walls, habitats, etc.)
- Manufacturing and repair with in-situ resources (spare parts, wires, trusses, integrated systems etc.)
- Space utilities and power from space resources.

Numerous studies have shown that making propellants in-situ can significantly reduce mission mass and cost, and also enable new mission capabilities, such as permanent manned presence and surface hoppers. Experience with the Mir and International Space Station and the recent grounding of the Space Shuttle fleet have also highlighted the need for backup caches or independent life support consumable production capabilities, and a different paradigm for repair of failed hardware from the traditional orbital replacement unit (ORU) spares and replacement approach for future long duration missions. Lastly, for future astronauts to safely stay on the Moon or Mars for extended periods of time, surface construction and utility/infrastructure growth capabilities for items such as radiation protection, power generation, habitable volume, and surface mobility will be required or the cost and risk of these missions may be prohibitive. To evaluate the benefits, state-of-the-art, gaps, risks, and challenges of ISRU concepts, seven ISRU capability elements were defined and examined: (i) resource extraction, (ii) material handling and transport, (iii) resource processing, (iv) surface manufacturing with in-situ resources, (v) surface construction, (vi) surface ISRU product and consumable storage and distribution, and (vii) ISRU unique development and certification capabilities.

When considering the impacts and benefits of ISRU, mission and architect planners need to consider the following five High Criticality-to-Mission Success/Cost areas that are strongly affected by ISRU during technology and system trade studies

- Transportation (In-space and surface)
- Energy/Power (electric, thermal, and chemical)
- Life Support (radiation protection, consumables, habitable volume, etc.)
- Sustainability (repair, manufacturing, construction, etc.)
- Commercialization (costs are transitioned to the private sector initially or over time)

Benefits of ISRU for Missions and Architectures

Incorporation of ISRU capabilities can provide multiple benefits for individual missions and/or architectures as a whole. The table below summarizes how many of these benefits can be achieved with inclusion of ISRU in missions.

Benefit	**Description**
Mass Reduction	In-situ production of mission critical consumables (propellants, life support consumables, and fuel cell reactants) significantly reduces delivered mass to surface, and therefore reduces delivered mass to Low Earth Orbit (LEO)
	Shielding for habitat (radiation, micrometeroid, and exhaust plume debris) and surface nuclear power (radiation) made from in-situ materials (raw or processed) significantly reduces delivered mass to surface.
	Delivered mass for sustained human presence significantly reduced through surface manufacturing and construction of infrastructure
Cost Reduction	Reduction of delivered mass leads to reduction in launch costs through smaller launch vehicles or reduced number of launches per mission
	Reuse of elements by resupplying consumables may lead to reduction in architecture costs
	Use of modular, common hardware in propulsion, life support, and mobile fuel cell power systems leads to reduction in DDT&E costs and reduced life cycle costs by reducing logistics
	ISRU enables reduction in architecture costs through access to multiple surface sites from a single landing site, thus eliminating the need for multiple launches.
	ISRU enables direct Earth return eliminating need for rendezvous and development of Earth Return Vehicles
	ISRU capabilities reduce architecture life cycle costs
	Cost reduction through commercial sector participation
Risk Reduction & Mission Flexibility	Reduction in mission risk due to reduction in Earth launches and sequential mission events
	Mission risk reduction due to surface manufacturing and repair
	Reduction in mission risk due to dissimilar redundancy of mission critical systems
	Reduction in mission and crew risk due to increased shielding
	Increased mission flexibility due to use of common modular hardware and consumables
Mission Enhancements & Enabled Capabilities	Increased robotic and human surface access through ISRU enabled hoppers
	Increased delivered and return payload mass through ISRU
	Reduced cost missions to Moon and Mars through in-space depots and Lunar delivered propellant
	Energy-rich and extended missions through production of mission consumables and power
	Low-cost mass-efficient manufacturing, repair, and habitation and power infrastructure growth

Mass Reduction Benefits

- *In-situ production of mission critical consumables (propellants, life support consumables, and fuel cell reactants) significantly reduces delivered mass to surface.* Depending on the destination and rendezvous location assumed for a mission, propellant for ascent vehicles can range from 8000 to 15,000 kg for Lunar ascent, to 26,000 to 39,000 kg for ascent for Mars orbit rendezvous, to 100,000 kg for direct return to Earth from the Mars surface. Also, use of ISRU to provide backup life support caches on the order of 7000 to 28,000 kg have been considered for Mars missions. Studies have shown[2,3,4] that for every kg of payload delivered to the Mars surface 3.5 to >5 kg are required in LEO, depending on whether a nuclear or chemical rocket trans-Mars injection stage is used. Similar ratios exist for the Moon. For example, for Mars Design Reference 3, 26,000 kg of propellant and 23,200 kg of water, 4500 kg of oxygen, and 3900 kg of buffer gas were made using 5420 kg of Earth supplied hydrogen and 3900 kg of ISRU plant mass. Based on the mass to LEO vs mass to Mars surface ratios above, using ISRU saved between 169,000 to 241,400 kg launched to LEO! The mass of the surface power plant was not considered in the mass savings calculations since propellant production occurs before crew arrival and the same power system is used for habitat power needs once the crew arrives.

- *Shielding for habitat (radiation, micrometeroid, & exhaust plume debris) and surface nuclear power (radiation) from in-situ materials (raw or processed) significantly reduces delivered mass to surface*. At this time, the only criterion for astronaut radiation protection is “As Safe As Reasonably Achievable” (ASARA). Under this guideline, the mass of shielding launched is balanced with the acceptable risk for crew exposure to solar events and general cosmic background radiation. As surface mission durations increase, the accumulated risk to crew also increases. The ability to use in-situ materials (either raw regolith or refined products such as water) for radiation shielding would reduce the exposure that is considered ‘acceptable’. During development of the Transhab, a storm shelter using a water tank surrounding the crew quarters was under consideration. Analysis led to an optimal water thickness of 2.26 inches[5]. Assuming that the crew quarters fit in a cylinder 5 m in diameter and 3 m tall, the water volume of this shield is ~5.1 m^3 which is equivalent to 5100 kg. If the hardware and infrastructure used to create habitat shielding, or shielding around emplaced nuclear reactors or landing pads was the same as that used for in-situ propellant production, the ‘additional’ launched mass to enable much greater protection is negligible.

For exhaust plume debris, Apollo style landings on the Moon showed ejecta occurred but did not threaten the LEM which was ~18 MT. However, examining the Surveyor lander after the Apollo 12 LEM landed showed that plume debris did strike the Surveyor III[6]. With current designs for Lunar landers weighing a minimum of 28 MT, ejecta debris and landing pad stability will need to be addressed.

- *Delivered mass for sustained human presence significantly reduced through surface manufacturing and construction of infrastructure.* The long-term presence of humans on the surface of the Moon and Mars will require a growth in infrastructure beyond the initially deployed habitat and surface power elements. ISRU can enable significant reductions in long term launch mass and costs through the ability to fabricate in-situ habitat and power systems, replace failed or worn parts and equipment, and create new items on an as-needed basis. For example, ISRU can reduce launch costs by a factor of 10 for in-situ construction of electrical power generation systems in 1MW class compared to Earth delivered hardware[7].

Cost Reduction Benefits

- *Reduction of delivered mass leads to reduction in launch costs.* Reduction in mass required to be delivered to planetary surfaces will impact launch costs in one of two ways, either fewer launches will be required to support a mission or a smaller launch vehicle can be used. Elimination of launches would lead to greater architecture cost savings.

- *Reuse of elements by resupplying consumables leads to reduction in architecture costs.* Recurring costs for the Apollo Command & Service Module (CSM) and Lunar Excursion Module (LEM) were approximately $294M and $651M respectively (est. FY05 dollars)[8]. Even though future Crew Exploration Vehicle and Lunar ascent/descent vehicles are not expected to cost this much, they are expected to be in the $10’s M to low $100,s M. The extra cost of designing and certifying systems for reasonable reuse before discarding (5 to 10 times) can possibly provide significant immediate and long-term savings compared to missions and architectures based on non-reusable hardware. In-situ production of propellants makes lander/hopper reuse possible without the extra cost of launching and pre-positioning propellant depots from Earth. Further analysis of the development and recurring cost of limited reuse vs expendable transportation assets is recommended.

- *Use of modular, common hardware in propulsion, life support, and mobile fuel cell power systems leads to reduction in DDT&E costs and reduced life cycle costs by reducing logistics.* A significant number of the technologies, components, and subsystems associated with in-situ resource utilization are analogous to life support, fuel cell power, and propulsion systems. Examples include valves, water electrolyzers, phase separators, heat exchangers, and gas and cryogenic storage. With pre-planning and good systems engineering, a large number of these common components and subsystems could be used in multiple systems. Understanding of processing/usage rate requirements can further lead to development of modular, interchangeable components and replacement units that can also support logical redundancy levels or degraded modes of operation with failure if sized properly. Example: a single liquid oxygen tank design could support an EVA suit, and multiples of this same tank could be used on EVA rover assistants and surface mobility rovers, thereby eliminating separate tank DDT&E costs. This common tank also provides system robustness and reduced logistics costs by allowing a small number of spares to support multiple systems and allow for scavenging and cannibalization of non-critical systems to support repair of critical system failures.

- *ISRU enables reduction in architecture costs through access to multiple surface sites from a single landing site, thus eliminating the need for multiple launches.* In-situ propellant production, combined with reusable systems such as hoppers, can be used to extend surface exploration without the need for separate dedicated missions. In a recent study[9], it was estimated that a Lunar oxygen production plant, a reusable lander, and a single lander mission delivering methane or hydrogen fuel from Earth (Lunar water processing was not assumed) could enable 8 (methane fuel) to 14 (hydrogen fuel) hopper excursion missions to different locations on the Moon. If one assumed a single lander was required for the Lunar oxygen production plant emplacement, ISRU would eliminate the need for between 6 to 12 dedicated surface exploration missions, each costing $B's. Another example is a Mars science lander/hopper with a propellant production plant. After completion of the initial landed mission, the lander could hop to a second location. If successful, the science value obtained would be doubled. A slightly different scenario would have the mission initially land at a reasonably 'safe' location, than hop to a higher risk area after initial science was obtained.

- *ISRU enables direct Earth return eliminating need for rendezvous and development of Earth Return Vehicle*. Studies have shown that in-situ propellant production for return vehicles can enable direct return to Earth from the surface of the Moon and Mars [10,11,12] . In these studies, the need to develop, launch, and rendezvous with a separate Earth Return Vehicle was eliminated, thereby reducing both cost and mission risk by eliminating a critical mission phase.

- *ISRU capabilities reduce architecture life cycle costs*. Most mass sent for ISRU production will provide a high mass payback over time. For example, a 10 MT process plant producing 650 MT of oxygen over a years time has a mass payback ratio of 65:1. Systems with high mass payback ratio significantly reduce mass transport requirements over the lifecycle of the system. More advanced process plants which produce a range of products but require more advanced infrastructure coupled with space manufacturing and integration, allow non-linear growth of surface and space infrastructure. In the near term, local integration technology enables repair at the component level as opposed to the system level. This allows better use of the mass budget that would have gone to spare parts. This also increases the probability of mission success. Once in place, these ISRU capabilities will retain production capability and will be able to expand infrastructure. All of these factors coupled with the ability to reuse surface and transportation vehicles with ISRU provided consumables can contribute to significantly reduced life cycle costs compared to non-ISRU missions.

- *Cost reduction through commercial sector participation*[13,14,15,16]. The economic development of the Moon meets and enables strategic goals of the Vision for Space Exploration. The primary purpose of

ISRU is to reduce the mass, cost, and risk of human exploration while also enabling new mission concepts. If there were more ‘customers’ besides NASA for ISRU products and services, the development and deployment costs to NASA could be significantly reduced. Initially, NASA and the commercial sector could cooperate to emplace and operate plants (either robotic or human operated) with an orderly transition to commercial production of propellant and other products for use on the Moon or on Mars missions. Additional ISRU plants could be designed and built by private enterprise, and propellant and other products could be purchased by NASA (or other commercial entities) at the Moon for use as needed. Commercialization can provide added capital that NASA can leverage with its own fixed budget to respond to opportunities, facilitate and nurture commercial ventures, and augment human exploration capabilities. In the long-term, Lunar industrial plants may produce electrical power through solar energy conversion for eventual use on Earth, or helium-3 production could allow large-scale fusion reactors to become feasible on Earth.

Risk Reduction & Mission Flexibility Benefits

- *Reduction in mission risk due to reduction in Earth launches and sequential mission events.* Missions are made up of a large number of sequential events which all must be successful for the mission to be a success. The total risk to mission success is the product of the risks associated with each sequential event. The greater number of events, the higher the total mission risk. The use of ISRU can potentially eliminate the number of launches required to complete the mission, or enable direct return to Earth, thereby eliminating rendezvous events required for non-ISRU missions.

- *Mission risk reduction due to surface manufacturing and repair*. Experience with Mir, International Space Station (ISS), and Shuttle, have shown that even with extensive ground checkout, hardware failures occur. For long duration missions, such as Mir and ISS, orbital replacement units (ORUs) must be stored on-orbit or delivered from Earth to maintain operations, even with systems that were initially two-fault tolerant. Long surface stays on the Moon and Mars will require a different method of failure recovery than ORU’s. The long trip times and the 26 month gap in launch windows for Mars missions, along with the goal of minimizing delivered mass to Mars, will make use of ORU failure recovery impossible. The ability to provide in-situ fabrication and repair of spare and replacement parts is required to reduce the risk to crew and increase long-term mission success probabilities.

- *Reduction in mission risk due to dissimilar redundancy of mission critical systems.* Redundancy is the preferred method of ensuring system reliability, robustness, and mission success. However, redundancy based on use of common components and parts can still lead to system loss due to common failure modes (example, contamination from carbon dioxide sorbent beds on ISS fouling downstream valves). Experience with ISS has shown that dissimilar life support systems provided by the US and Russians have enabled continuous operation when either system has failed. The ability to produce and store life support consumables from in-situ resources can provide the dissimilar redundancy necessary for long duration human planetary surface exploration. In addition, the ability to fabricate energy-producing elements (electric, thermal, and chemical) from in-situ resources not only provides for an energy-rich environment, but also increases safety margins by reducing reliance on Earth delivered hardware.

- *Reduction in mission & crew risk due to increased shielding.* As stated under Mass Reduction Benefits, the mass of radiation shielding launched is balanced against the acceptable risk for crew exposure to solar events and general cosmic background radiation. As surface mission durations increase, the accumulated risk to crew also increases. The ability to use in-situ materials (either raw regolith or refined products such as water) for radiation shielding would greatly reduce the exposure that is considered ‘acceptable’. The ability to provide shielding around emplaced nuclear reactors or landing pads would also reduce the acceptable deployment distance from crew operation areas. If the reactor needs to be deployed (as seems likely), the greater the distance required, the greater risk to deployment success. Surface mobility units for ISRU could be used for reactor deployment in addition creating berm shielding to lessen the deployment distance.

- *Increased mission flexibility due to use of common modular hardware and consumables.* The use of common module hardware and common consumables, as stated under Cost Reduction Benefits can also increase mission flexibility by extending surface operations and providing failure recovery options. For example, if an EVA robotic assistant is utilizing oxygen and methane for fuel cell power, should an EVA need to be extended, the astronaut could scavenge oxygen and fuel cell reactants from the robotic assistant for the EVA suit. Also, the EVA rover can include an umbilical to replenish EVA suits while traversing to the next site of exploration. Should a component on the EVA suit fail, scavenging and cannibalization of parts is possible.

Mission Enhancements & Enabled Capabilities

- *Increased robotic and human surface access through hoppers.* As stated under *Cost Reduction Benefits,* in-situ propellant production combined with hoppers can be used to extend surface exploration through access to multiple surface sites from a central base, thus eliminating the need for multiple launches. .

- *Increased delivered and return payload mass through ISRU.* When and how ISRU capabilities are introduced into mission architectures can significantly impact both delivered and return payload mass capabilities. For example, a lander that is designed to carry a fully fueled ascent vehicle for initial human missions can carry an increased payload mass to the surface equal to the ascent propellant load if in-situ propellant production is incorporated in subsequent missions.

- *Reduced cost missions to Moon and Mars through in-space depots and Lunar delivered propellant.* The use of mission staging points for future human Lunar and Mars exploration missions in Earth Orbit and Earth-Moon libration points has been considered due to increased flexibility in Lunar surface site access and reduced time between launch/mission window opportunities. The establishment of a propellant depot at the Earth-Moon L_1 or L_2 libration point has the potential to significantly reduce the Earth launch vehicle lift-off weight (~2/5) compared to the non-depot option based on the significant reduction in mission Delta-V (ΔV) for propellant delivered from Earth to L_1 compared to the ΔV from the Lunar surface to L_1 (~1/5)[17]. Not only do the Earth launched transportation vehicles avoid carrying the return propellant, but also the extra propellant required to transport the return propellant. A quick analysis of a human Mars mission using hydrogen and oxygen fuel from Lunar polar water delivered to LEO from the Lunar surface (using in-situ derived propellants for all stages) showed a potential 40% reduction in Earth to LEO payload required to support the mission[18]. Further analysis comparing the entire proposed system (including tanker and depot infrastructure) against conventional mission concepts is required.

- *Energy-Rich and extended missions through production of mission consumables and power.* Until ISRU is adequately demonstrated, mission planners will be hesitant to incorporate ISRU into mission critical roles in future human missions. One way to provide this confidence while providing immediate mission payback is to incorporate ISRU into early robotic and human missions to produce mission consumables that can then be used to extend the original mission duration. Examples include separation and capture of Mars atmospheric gases to extend science instrument use and in-situ production of oxygen to allow additional EVA’s or surface stay duration. In particular the in-situ regeneration or production of fuel cell reactants for science/human rovers to provide a power-rich environment may be critical to enable the science required to justify the cost and risk of the mission. The ability to pre-deploy hardware to fabricate energy-producing elements in-situ could also provide an energy-rich environment for subsequent robotic and human missions.

- *Low-cost mass-efficient manufacturing, repair, and habitation & power infrastructure growth.* The benefits of ISRU extend beyond production of propellants, fuel cell, and life support consumables. Carbon dioxide can be extracted from the Lunar regolith or the Mars atmosphere to support plant growth for food. Laboratory demonstrations have shown that it will be possible to fabricate bricks and panels from local materials and use them for constructing habitats, workshops, storage buildings, and ground transportation infrastructure. Metals and manufacturing and construction feedstock can be extracted from local rocks and soil to make beams, wires, and solar electrical and thermal power generation and storage systems. Much of the essential materials needed for life on the new frontier can be produced from local resources. Delivery of all of this hardware from Earth would be cost prohibitive for long term presence on the Moon or Mars. These ISRU capabilities allow for infrastructure growth on an as-needed basis instead of having to plan a decade in advance for delivery of the infrastructure assets.

Key Architecture & Strategic Decisions For ISRU

Strategic Decisions

Architecture/Strategy

Key Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
When will ISRU be used on human missions and to what extent?	2005 to 2012 Early Robotic Exploration	Determines need for 'prospector' and demonstration missions. Determines location of exploration and transportation architecture.
To what degree will Mars requirements drive Lunar design selections, i.e. propellants	2005 to 2008	Determines if Lunar landers utilize the same or different propulsion elements.
Level of reusability: single-use vs multiple-use elements	2010 to 2012	Determines whether one or two landers will be developed for Lunar operations
Level of commercial involvement	2005 for 2010 Early Robotic Exploration	Determines long term NASA funding needs. Early involvement required for legislation and maximum benefit
Is long-term human presence on the Moon a goal?	2010 to 2015	Determines if Lunar ISRU is only a precursor for Mars, and determines relevant technologies and operating environments
Is water readily available on the Moon for propellants and life support?	2010 to 2012	Determines long term sites for Lunar bases and transportation architecture
Is water readily available on Mars for propellants and life support?	2010 to 2015	Determines sites for human Mars exploration and extent of ISRU use on Mars.

- *When will ISRU be used on human missions and to what extent*? In most major mission and architecture studies performed in the last decade or two, the use of ISRU has been more a matter of 'when' than 'if'. Since no dedicated ISRU demonstration or mission has yet been flown, mission planners are reluctant to baseline an 'unproven' technology for the first missions to the Moon and Mars because of the perceived risk. This is the case even though some of the technologies (and often the actual hardware) for propellant production from the Mars atmosphere are similar to those being considered for use in regenerative life support systems (i.e. sabatier reactor, water electrolysis, carbon dioxide capture and separation, etc.) and the duration of ISRU systems is 300 sols versus over 1000 days for round-trip life support systems. As will be highlighted in the Strategic and Architecture Decisions below, how early and to what extent ISRU is incorporated into mission plans can have a significant impact on individual elements as well as missions. It is therefore recommended that resource prospecting missions and ISRU demonstrations be performed as early as possible to obtain the greatest benefit and minimize element redesign.

- *To what degree will Mars requirements drive Lunar design selections*. At this time, oxygen and methane are the easiest propellants and fuel cell reagents to produce from in-situ resources on Mars. If water is readily assessable on Mars, besides making this propellant combination even more beneficial oxygen and hydrogen propellants are also candidates for Mars ascent vehicles. However, the power and complexity of storing liquid hydrogen under atmospheric conditions and the large volume impact on lander/ascent vehicle designs will make the use of hydrogen fuel challenging. In-situ production of methanol, ethylene, aromatics (benzene and toluene), and short-chain hydrocarbon mixtures from simulated Mars resources have also been demonstrated in the laboratory. These fuels may be easier to store than methane, but require more complex production methods and the yields are uncertain. Carbon monoxide is also a potential Mars produced fuel, however its low performance and low density cryogenic fluid characteristics limits it's applicability to hopper applications. If Lunar missions are required to demonstrate relevant technologies and systems for future human Mars missions, selection of the propellants for Lunar missions will need to be based on these propellant choices. Early demonstration of methane production from Lunar soils (solar wind implanted carbon and hydrogen or possible polar resources) may also be desirable.

- *Level of reusability: single-use vs multiple-use elements.* In-situ production and use of propellants, life support consumables, and fuel cell reagents provide the most immediate mass and cost benefits of ISRU for human and robotic exploration. However, the long-term sustainability of human exploration can only be achieved if transportation and surface elements are reused. The extent of reuse and when it is inserted into mission plans will drive need dates and production rates for ISRU. The level of reuse is particularly important for lander/ascent vehicle design and use. For the Moon, the ability to refuel and use a lander can enable single stage landers and surface hopper vehicles.

- *Level of commercial involvement:* Partnering with industry on development of space resources opens up the possibility of significant savings to NASA should other 'markets' be developed. However, for successful space commercialization to occur the introduction of technologies and capabilities will be driven by the 'business model', and the pace and scope of ISRU may be much different than for a NASA-only program. For NASA to obtain the greatest benefits of space commercialization, the US government and NASA must initiate multiple activities as soon as possible to address such challenges as anchor tenancy and service contracts, creating favorable space legislation and regulations (tax incentives, property rights, liability, ITAR / export control), initiating challenges & prizes, etc.

- *Is long-term human presence on the Moon a goal?* The current primary purpose of human Lunar exploration is for use as a testbed for human Mars exploration. However, if long-term presence on the Moon is also a goal, then ISRU technologies and capabilities that are applicable to both the Moon and Mars as well as those unique to Lunar ISRU should also be developed. In the case of technologies and capabilities applicable to both Moon and Mars, final selection may be non-optimal to either location, but may be lowest in development and delivered cost for both. As defined in the 'Benefits of ISRU' section of this report, ISRU can provide significant benefits for long-term human Lunar operations. However, due to the harsh Lunar environment and long development times required to go from concept to certified flight hardware, small proof-of-concept ISRU demonstrations should be considered early in the program to establish the feasibility of these benefits in a timely manner.

- *Is water readily available on the Moon for propellants and life support?* Whether water exists at the Lunar poles and can be extracted efficiently has profound implications on the extent and location of robotic and human exploration of the Moon as well as implications on future human Mars exploration architectures. Water provides both oxidizer and fuel for propulsion systems, and can define the degree of self sufficiency, radiation shielding, and closed-loop life support required to sustain humans in space. Water is also easy to store and transfer and can be easily delivered to multiple transportation nodes (surface, Earth-Moon L_1, Earth orbit, etc.) and electrolyzed at the final destination.

- *Is water readily available on Mars for propellants and life support?* As with the Moon, the availability and extraction efficiency of water on Mars will have a significant impact on the location and duration of human Mars surface exploration. The extraction and processing of water may require the pre-deployment of assets that will significantly influence the 'short vs long stay time' and 'abort-to-orbit vs abort-to-surface' architecture debates. Due to the time required to develop demonstrations and the 26 month launch window interval for missions to Mars, lessons learned from one mission can only impact the design phase of missions 2 or 3 launch opportunities later. Therefore, early understanding of water availability and extraction efficiency is required to ensure adequate development and certification of human-rated Mars water processing hardware. The presence of some bound water in Viking soil samples is documented, and recent data from Mars Odyssey suggest that water may be available all across the Mars surface at various depths and concentrations. Additional data on water resources will be obtained from the Mars Express, 2007 Phoenix, and 2009 Mars Science Laboratory (MSL) missions. The goals and objectives of water-based ISRU are consistent with the scientific objectives for the search for past life on Mars and the "follow the water" theme. However, the search for and use of deep underground liquid water for ISRU is given a much lower priority than access to surface (<1 meter) water in regolith due to its higher complexity of drilling, reduction in potential surface exploration locations, and the possibility of Mars life associated with underground liquid water sources (thereby eliminating its use as resource). The Mars Express mission has identified methane in the Mars atmosphere raising the possibility that concentrated sources of life or methane may be discovered.

Architecture Decisions

Architecture/Strategy

Key Architecture Decisions	**Date Decision is Needed**	**Impact of Decision on Capability**
Single Base w/ forays vs Multiple individual missions	2008 to 2012	Determines surface lander and habitat designs, and when and to what extent Lunar ISRU is incorporated
Pre-Deploy vs All-in-one Mission	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines size of lander/habitat and level of ISRU incorporation
Direct Return, Low Orbit Rendezvous, or L1/High Orbit Rendezvous	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines impact of ISRU propellant production on mission & architecture mass and cost.
Surface Power-Solar vs Nuclear	2009-2010 for Lunar base, 2015-2020 for Mars base	Determines size, operating duration, and cycle of ISRU plants
Abort-to-Surface or Abort-to-Orbit	2008 to 2012 for Lunar and 2015 to 2020 for Mars	Determines if use of ISRU propellant for ascent propulsion is acceptable

- *Single Base w/ forays vs Multiple individual missions.* The extraction and processing of resources will require both ISRU and power generation 'infrastructure'. A critical metric for measuring the benefit and impact of ISRU on missions is 'mass of product produced vs mass of ISRU infrastructure'. For ISRU to be mass beneficial, a value considerably greater than 1 is required and the more product produced, the greater the benefit of ISRU. For short duration human Lunar missions (<14 days) the mass of mission consumables and the risk of radiation events may be low enough not to warrant emplacement of ISRU hardware except if repeat visits are anticipated. For long duration Mars surface missions (>300 days), the production of backup life support consumables, fuel cell reagents, and consumables lost during EVA and airlock use plus the longer exposure to space radiation should be enough justification on its own for use of ISRU on early human Mars missions, even if propellant production is not included. Also, development of a single base instead of trips to multiple destinations allows for gradual growth in ISRU capabilities as needs grow (i.e., add an extra excavator or regolith processing unit to pre-existing units to increase production rate as well as provide redundancy). The growth in ISRU can lead to use of surface hoppers to meet the original goals of multiple individual missions to distinct landing sites.

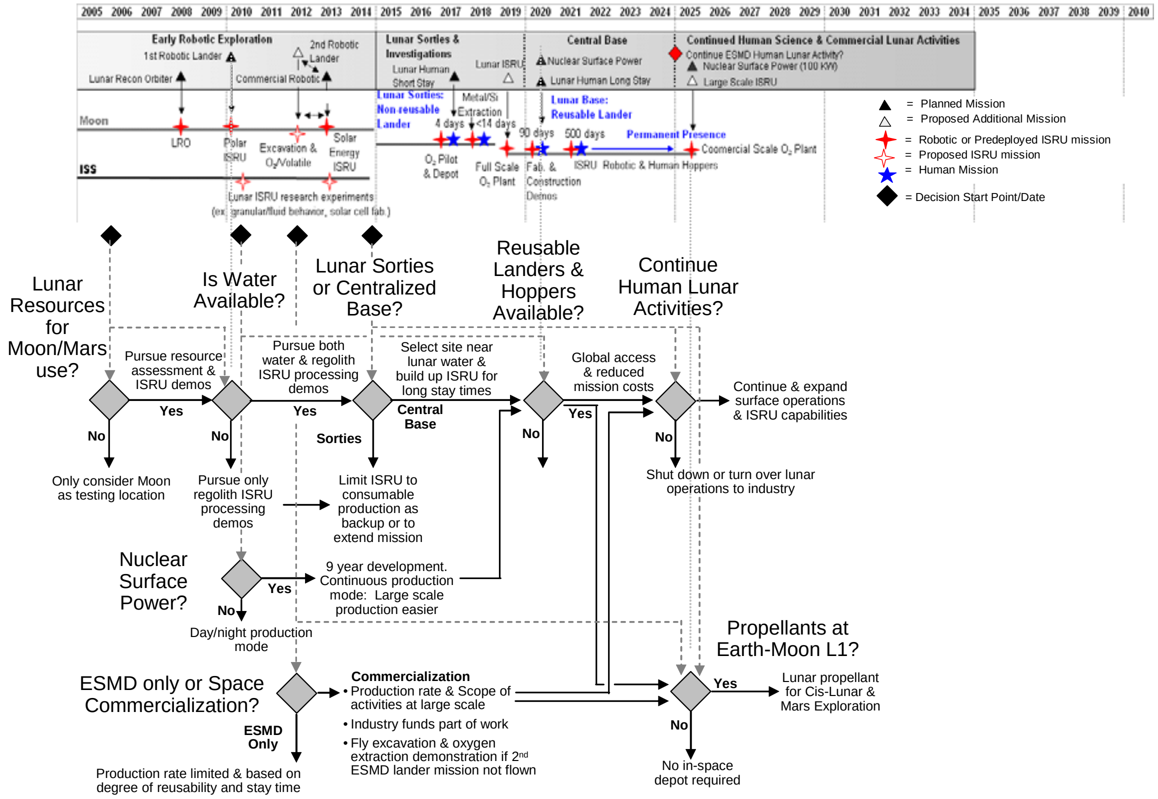
- *Pre-Deploy vs All-in-one Mission:* Some mission studies have recommended the delivery of everything needed to the surface in one vehicle to eliminate the need for precision landing as well as concerns with landing aborts if pre-deployed assets are critical for crew and mission success[19]. The size of ISRU plants are largely a function of the total production need and duration of production operations. To minimize the mass and size of the ISRU plant and power system, long production times are favored (this must be balanced against the increased risk of hardware failure with long production times). Pre-deployment allows for production durations to be long enough to minimize ISRU and power system mass requirements as well as allow for completion of mission critical ISRU production needs before crew departure from Earth. For an all-in-one mission to incorporate ISRU, the mission surface stay time must be long enough to allow for reasonable ISRU plant and power system mass requirements, and it must be recognized that the crew and mission are dependent on the real-time successful operation of ISRU and power systems. Since all missions are dependent on multiple systems working successfully, this may or may-not be a selection discriminator.

- *Direct Return, Low Orbit Rendezvous, or L_1/High Orbit Rendezvous.* The ascent propulsion requirements and rendezvous locations have a significant impact on transportation system design and technology trades. If in-situ propellant production is not incorporated into a mission, then low orbit rendezvous scenarios must be selected to minimize lander/ascent vehicle size. This requires an increase in both capture orbit propulsion needs and use of a separate Earth Return Vehicle. Like landers, the larger the Earth return stage, the larger the initial Earth departure stage needs to be, i.e. a 1 kg increase in Earth return stage in high Mars orbit equates to a minimum of 2.4 kg in LEO[4]. Use of in-situ propellant production can both reduce the landed mass (since ascent propellant is not carried to the surface), as well as enable much higher rendezvous orbits or even direct return to Earth from the planetary surface[10]. Going to higher rendezvous orbits reduces both the capture and Earth return propulsion needs, thereby making each stage smaller, and use of direct return to Earth eliminates both the need for rendezvous as well as development and launch of a dedicated Earth Return Vehicle.

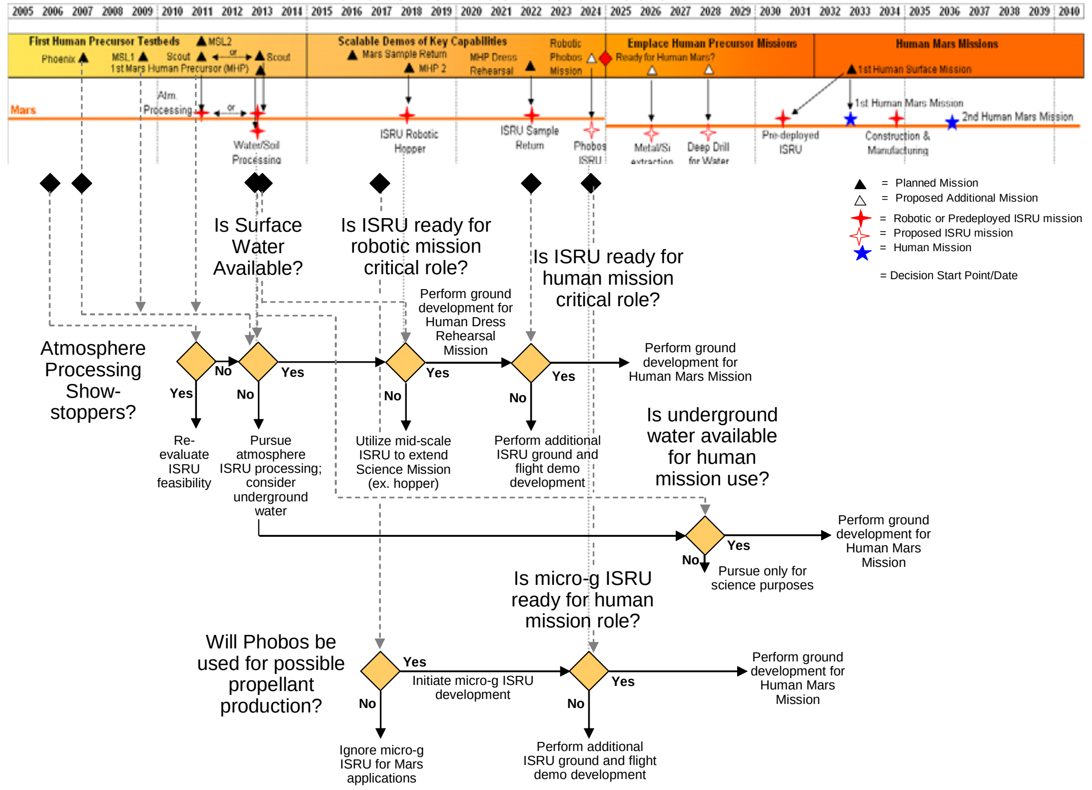
- *Surface Power-Solar vs Nuclear.* As mentioned previously the size of the required ISRU plant is based on the total production need and duration of operation. Because many ISRU processes are power-intensive, if solar power is utilized, initial operations will likely be possible only during sunlit durations. This means ~12 days for the 28 day non-polar Lunar day/night cycle and 6 to 8 hours for the ~24 hr Mars day (sol). Nuclear surface power can enable around-the-clock ISRU processing from the start. Therefore, for the same total production need, an ISRU plant using nuclear power may operate at half the production rate for a Lunar non-polar solar-powered ISRU system and at a third of the production rate for a Mars solar-powered ISRU system. However, the ability to manufacture power generation and storage systems in-situ, and the use of near-permanent sunlit locations on the Moon, could delay or eliminate the need for nuclear surface power on the Moon, except as possibly a test for future Mars applications. All of the ISRU power system production mass delivered to the Moon contributes to boot strapping the power system and will eventually produce a large payback ratio. Other systems such as thermal wells can also reduce or eliminate the need for nuclear power on the Moon if desired.

- *Abort-to-Surface or Abort-to-Orbit.* The Apollo LEM incorporated an ‘abort-to-orbit’ strategy in the event of a landing system failure. This was possible since the LEM was a two-stage lander with all mission propellant launched from Earth, and the Apollo CSM was available in low Lunar orbit. The use of in-situ produced propellants for ascent propulsion precludes the use of abort-to-orbit failure recovery. Instead, an abort-to-surface scenario is required to be compatible with ISRU.

Lunar ISRU Missions & Decision Points



Mars ISRU Missions & Decision Points



ISRU Emphasized Architectures for Moon and Mars

Reference Relevant Legacy Activities

Between 1986 and 1991, a number of prestigious studies were performed which highlighted the benefits of developing ISRU for use in the future human exploration and development of our solar system [Beyond Earth's Boundaries, Report of the 90 Day Study on Human Exploration of the Moon and Mars, Report of the Advisory Committee on the Future of the U.S. Space Program, America At the Threshold, etc.]. Since the early '90's, NASA, industry, and academia have performed a number of mission studies which have evaluated the impacts and benefits of ISRU. Results from a study comparing a Lunar architecture which emphasized early production and utilization of Lunar propellants (LUNOX study) versus a conventional Lunar exploration scheme (First Lunar Outpost study) indicated lower hardware development costs, lower cost uncertainties, and a ~50% reduction in human transportation costs for the ISRU-based mission architecture[20]. For Mars, sample return missions with in-situ propellant production as well as the human Mars Reference Mission[2,10,11] studies showed that ISRU could reduce Earth launch mass by >25%. More recently, the use of mission staging points for future human Lunar exploration missions shows increased mission flexibility and reduced mission mass are possible with use of Lunar in-situ produced propellants[17,18]. The recent Capability Roadmap activity has been the most intensive and complete to date for ISRU, however, much of the initial work was based on previous strategic planning and road-mapping activities performed for Technology for Human/Robotic Exploration And Development of Space (THREADS), Advanced Systems, Technology, Research, and Analysis (ASTRA), and the Capability Requirements, Analysis, and Integration (CRAI) programs.

Architectural Assumptions

The primary difficulty in executing the Capability Roadmap activity was the lack of defined mission objectives, goals, and dates for the robotic and human exploration of the Moon and Mars. Before the presentation to the National Research Council, the ISRU Capability Roadmap Team created its own 'notional' ISRU-Emphasized architecture to highlight potential ISRU-based missions and their logical sequence of events. This architecture was purposefully all-inclusive to ensure all options were captured. For this final report, the NASA APIO provided top-level mission objectives and dates. However, some additional missions have been added to this roadmap to provide a more logical and reduced risk implementation of ISRU into human Lunar and Mars missions. It is believed that these additional missions are consistent with the goals and objectives of current Lunar mission architecture options being considered by the Lunar Strategic Roadmap (Option C Early Lunar Resources) and the Mars Strategic Roadmap teams.

To develop the notional ISRU-Emphasized architecture and estimates of size and power for potential ISRU capabilities, the following architecture attributes were assumed:

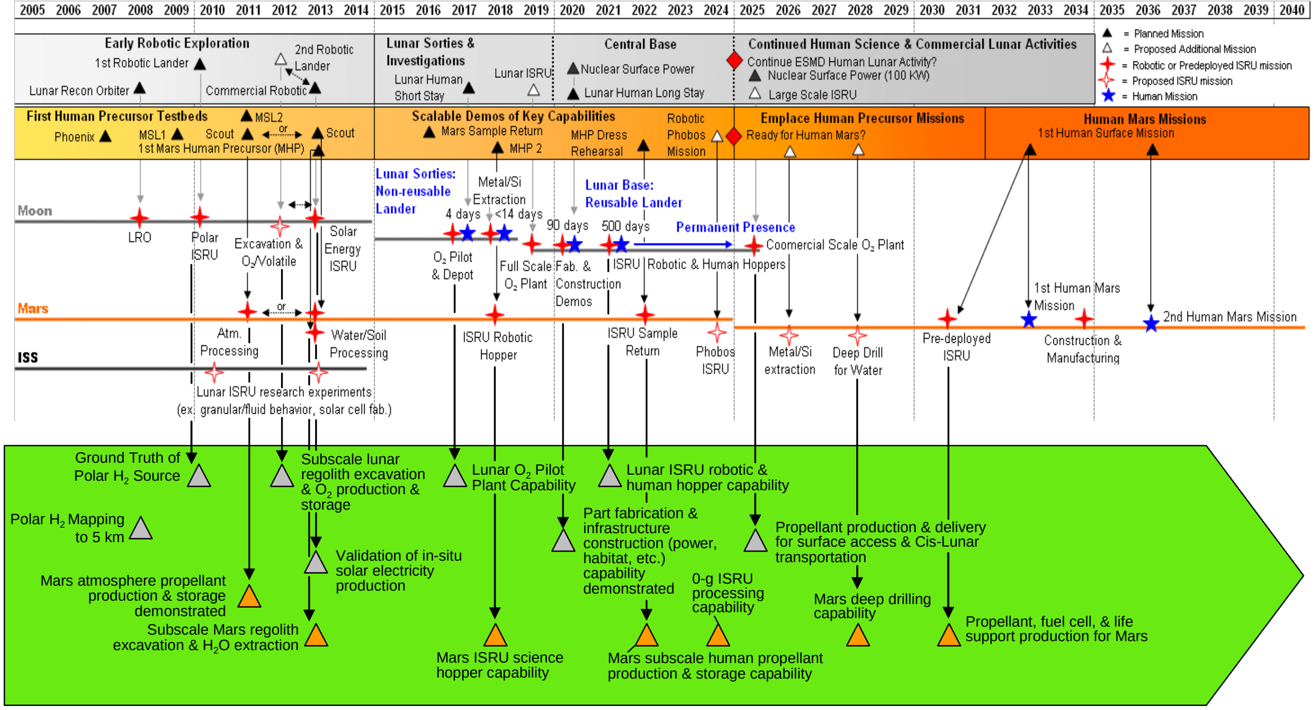
- No Earth launch vehicle assumption was made; benefits were based on reduction in LEO payload
- Crew of 4 or 6 assumed up to permanent presence; TBD (12) at permanent presence
- Need to characterize resource, surface environment, and engineering unknowns as early as possible
- Utilize ISS for ISRU-related research if available and logical
- Develop single robust primary Lunar exploration site(e.g. McMurdo Station approach) after limited number of initial checkout flights
- Demonstrate ISRU in Lunar Sortie and Investigation phase to support use of ISRU and reusable systems at the start of Central Base operations
- Develop Lunar infrastructure and operations to *enable* sustainable Lunar operations in parallel with a Mars exploration program

In addition to these mission/architecture assumptions, derivatives of the notional ISRU- Emphasized architecture were evaluated including:

- Direct Return – ISRU Architecture
- Earth-Moon L_1 propellant for Moon/Mars
- ISRU-Commercial Architecture Aimed At All Government & Commercial Applications

Below is the latest notional ISRU-Emphasized architecture with start dates for initial ISRU capabilities identified.

Architecture & ISRU Capability Timeline



Incorporation Strategy

The ability to harness and utilize space resources to create products and services requires extra hardware and power but less volume and lift-off mass when compared to missions that bring everything from Earth. It is critical that early missions require the minimum of pre-deployed or delivered hardware and power infrastructure while providing immediate mass and cost benefits. To minimize the cost and risk of incorporating ISRU into missions, an evolutionary approach in technology and scale is assumed. Each design/demonstration activity needs to build on lessons learned from previous work and show clear benefit metrics. Early hardware needs to be achievable (not optimized) and scalable to future missions and base growth. Also, until mission planners have confidence in ISRU, technologies and capabilities may need to be flight tested on robotic precursor missions or pre-deployed before insertion into the critical path for human missions. Once a central exploration base is selected, ISRU incorporated into missions must ensure a constant delivery of products, with incremental growth in both number of products and quantity of products. Capability elements need to be sized based on long-term mission objectives to allow incremental growth through delivery of extra elements or in-situ production with the growth and expansion of surface activities. Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capabilities.

Objectives of Lunar ISRU

There are three primary objectives for Lunar ISRU: 1. Identify and characterize resources on the Moon, especially the polar region; 2. Perform early demonstrations of ISRU on the Moon in preparation for human exploration of Mars; and 3. Develop and evolve Lunar ISRU capabilities to support sustained, economical human space transportation and presence on the Moon.

For preparation for human exploration of Mars, one main goal for early Lunar robotic and human ISRU missions is to demonstrate concepts, technologies, & hardware that can reduce the mass, cost, & risk of human Mars missions as early as possible. These include: (a) Excavation and material handling & transport, (b) Oxygen production and volatile/hydrogen/water extraction, (c) Thermal/chemical processing subsystems, and (d) Surface cryogenic fluid storage & transfer. Tests of these items on the Moon would provide evaluation of hardware under realistic environmental conditions not possible on Earth, but potentially at a lower cost then Mars missions. Since these concepts, technologies, and hardware are applicable to both the Moon and Mars, early demonstrations also supports sustained human presence on the Moon. The second major objective of early Lunar ISRU demonstrations is to obtain operational experience and mission validation for future Mars missions. Areas of particular importance for experience and mission validation include: (a) Pre-deployment & activation of ISRU assets, (b) Making and transferring mission consumables, such as propellants, life support, power reactants, etc., (c) Landing crew with pre-positioned return vehicle or 'empty' tanks, and (d) 'Short' (<90 days) and 'Long' (300 to 500 days) Mars surface stay dress rehearsals including part manufacturing and construction. Experience with pre-deployment and activation of ISRU is critical for Mars ISRU and the ability of astronauts to evaluate operations, correct early failures, and potentially return hardware to Earth for evaluation makes demonstrations on the Moon extremely attractive. The making and transferring of mission consumables and landing near pre-positioned ISRU with empty tanks are critical demonstrations in providing the confidence need by mission planners to incorporate ISRU early in human Mars missions. These capabilities are essential in achieving the maximum benefits of ISRU.

To support sustained human presence on the Moon, it is essential to develop and evolve Lunar ISRU capabilities that enable new exploration capabilities, such as long-range surface mobility, global science access, power-rich distributed systems, enhanced radiation shielding, etc. For this to be economical and allow continued presence on the Moon while going on to Mars, a space transportation system based on ISRU, reusable transportation assets, and single stage lander/ascent vehicles is required. Further cost benefits to NASA can be achieved if *government-commercial* space commercialization initiatives are started as soon as possible.

Objectives of Mars ISRU

There are three primary objectives for Mars ISRU: 1. Perform initial research and development of ISRU and characterize resources on Mars, especially water, in preparation for human exploration; 2. Develop and evolve Mars ISRU capabilities to reduce the cost, mass, and risk of human Mars exploration and enable new missions, 3. Enable human exploration beyond Mars.

For preparation for human exploration of Mars, Earth-based, ISS, and Lunar ISRU development, testing, and experience must be utilized to maximum extent possible. Also, characterizing the presence and extraction of Mars water as early as possible is critical, since both the benefits and risks are much greater compared to atmospheric processing alone for in-situ consumable production.

Until mission planners are confident in ISRU, demonstrations are recommended in a step-wise approach to increase confidence in environment/resource understanding and reduce mission application uncertainties. Also, ISRU capabilities that enable new exploration options, such as reduced size lander/ascent vehicles, surface mobility and hoppers, power-rich distributed systems, enhanced radiation shielding, manufacturing/construction, etc. should be pursued in an evolutionary approach. Early demonstrations are required due to long experiment development time (~4 years), the 26 month gap between mission launch window opportunities, long trip times, and extended surface operations. Lessons learned from one mission can only influence missions 2 or 3 opportunities (4 or 6 years) later. Because of this, parallel investigations of atmospheric and regolith/water-based processing with convergence to an end to end ISRU demonstration before a human mission is recommended.

It should be noted that every effort should be made to synergize future science and human precursor missions, especially with respect to ISRU. Small demonstrations (20 to 30 kg) on early SCOUT missions can provide immediate Mars ISRU design and operation experience (2011 or 13), and later Human Precursor ISRU missions can provide expended or enabled science objectives (2018 and/or 2022).

Mars ISRU may also be critical to enable human exploration beyond Mars. Use of propellant production from Phobos/Deimos, or resupply of propellants at a Mars-Sun L1 depot from Mars, may provide the logistics needed for long-term human exploration of the asteroid belt and beyond.

ISRU and Space Resource Commercialization[13,14,15,16]

- *ISRU enables commercialization.* The technologies needed to extract propellant and material products for NASA missions will lead to a wide range of products and services that can become the economic foundation of a sustainable and growing space economy. The government investment in ISRU technology can reduce the technical risk associated with entrepreneurial space ventures. Strong analogies to the early US aircraft industry are available, where the government played a leading role in enabling commerce by supporting technology development and by creating an early market for the delivery of airmail.

- *Commercialization enables ISRU.* Industrial expertise in mining, material extraction, process control and other areas will be the foundation of ISRU. The vast reservoir of technical experience within the US industrial base will serve as the basis for building tools and capabilities for planetary surface exploration and development. In addition, the technologies required for lunar exploration and development will be used to improve products and services on Earth, such as efficient mining techniques or reducing the size of processing systems, thereby opening new markets and strengthening US industrial productivity. By engaging commercial partnerships, a win-win situation will be created that benefits industry as well as NASA. Early engagement is the key to enable productive partnerships.

- *NASA Strategic Goals.* The economic development of the Moon meets and enables strategic goals of the Exploration Vision. ISRU development can promote commercial participation in exploration to further US economic interests. Commercial activities could provide products and services supporting reusable space transportation and exploration missions. Commercially supported ISRU offers a clear path to reusable, evolvable, extensible and sustainable space systems and capabilities.

- *Transcending budget restrictions.* Commercialization can provide added capital as well as capability to NASA. By facilitating and nurturing commercial ISRU ventures, NASA can leverage its budget by creating a channel to access private capital. The potential for off-budget augmentation of human exploration capabilities exists in many areas of ISRU with commercial potential. In addition, while the NASA budget is fixed, private capital is flexible in its ability to respond to opportunities.

- *Enabling human Mars exploration.* Converting lunar activities to an industrial basis could provide a path that enables NASA to transition its budgetary resources from human lunar to Mars exploration while achieving the goal of lunar base sustainability. Early engagement of industry will be required in order to maximize the likelihood of long-term economic sustainability of a lunar base.

- *NASA is a key facilitator* of economic development policy and law, and could serve as an enabling voice promoting legislation for rational space resource development. Proactive opportunity management could activate a rich set of early commercial ISRU capabilities that could benefit human space exploration and enhance U.S. economic interests. Sustainable ISRU enterprises will by definition expand to markets well beyond human space exploration. NASA must develop a due-diligence capability in order to anticipate and critically evaluate future business opportunities.

- *Partnerships are already forming.* Empowered by the strength of the exploration vision, a Boeing-lead aerospace consortium will be conducting a set of three non-traditional industry assessment workshops over the next year. The goal of these workshops is to establish communication, identify emerging opportunities aligned with ISRU and human space exploration, and engage the wealth of business experience that lies within non-traditional industry. The potential for early access to significant sources of private capital is another possibility, but will depend on the business cases identified as well as government willingness to support innovative partnership arrangements.

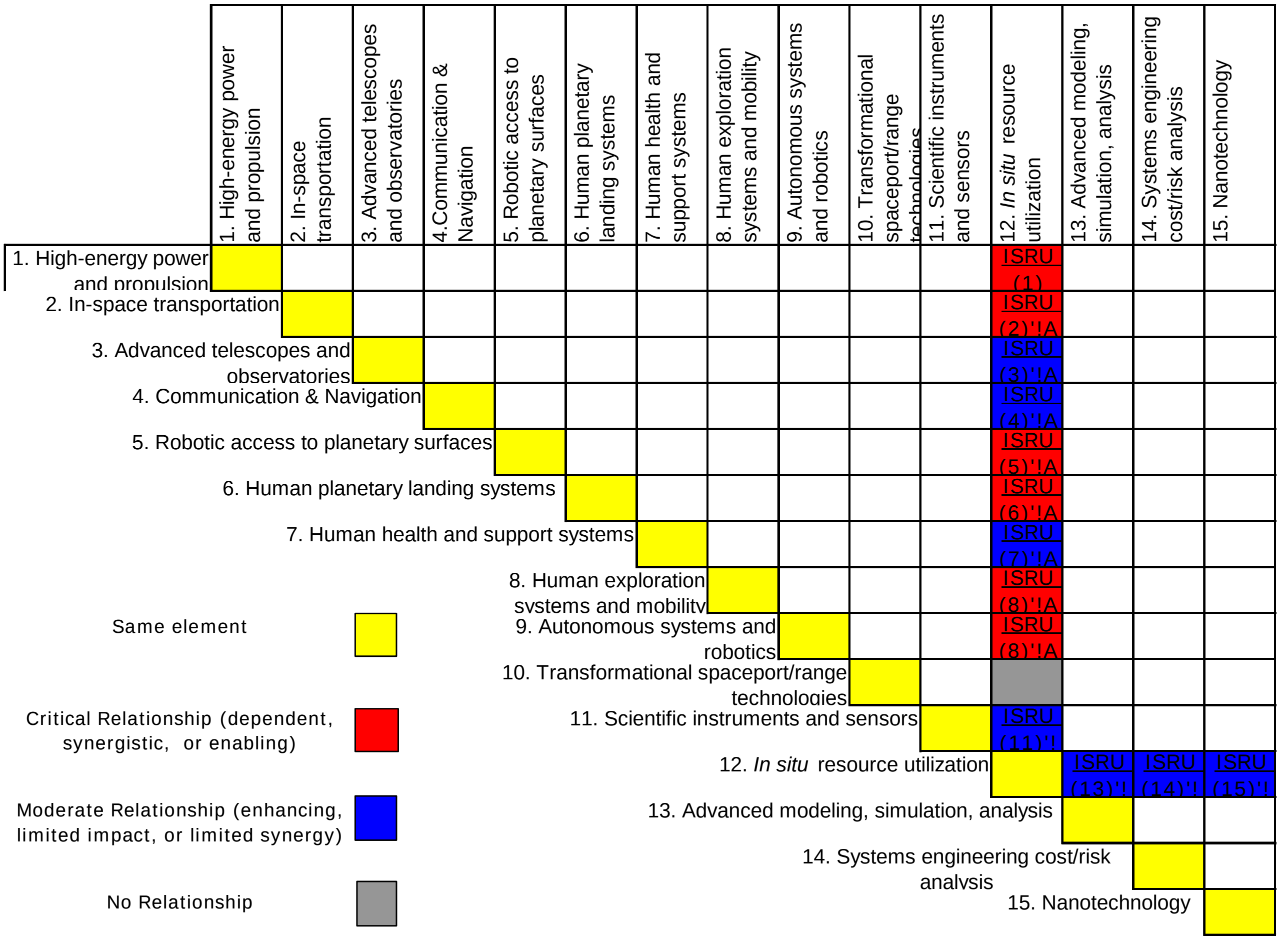
Critical/Enabling ISRU Capabilities

The Key Capability table below for ISRU was compiled after a multi-step process. First past ISRU technology and mission studies and reports were examined to identify ISRU capabilities and quantify the benefits of these capabilities to extending or enabling individual missions and complete architectures. Then the identified capabilities were compared to each other to determine relative ranking. The capabilities/sub-capabilities listed in the table were those that were identified as supporting multiple ISRU capabilities (ex. Excavation and Surface Cryogenic Fluid Storage), that are applicable to both the Moon and Mars, or are critical for achieving significant mass, cost, and/or risk reduction benefits for individual missions or architectures as a whole.

Key Capabilities and Status

Capability/Sub-Capability	**Mission or road map Enabled**	**Current State of Practice**	**Need Date**
Lunar/Mars Regolith Excavation & Transportation	All Lunar ISRU and Mars water, mineral extraction, & construction ISRU.	Apollo and Viking experience and Phoenix in 2007. Extensive terrestrial experience	2010 (demo) 2017 (pilot)
Lunar Oxygen Production From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Earth laboratory concept experiments; TRL 2/3	2012 (demo) 2017 (pilot)
Lunar Polar Water/Hydrogen Extraction From Regolith	Sustained Lunar presence and economical cis-Lunar transportation	Study & development just initiated in ICP/BAA	2010 (demo) 2017 (pilot)
Mars Water Extraction From Regolith	Propellant and life support consumable production w/o Earth feedstock	Viking experience	2013 (demo) 2018 or 2022 (subscale)
Mars Atmosphere Collection & Separation	Life support and mission consumable production	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Mars Oxygen/Propellant Production	Small landers, hoppers, and fuel cell reactant generation on Mars	Earth laboratory & Mars environment simulation; TRL 4/5	2011 (demo) 2018 or 2022 (subscale)
Metal/Silicon Extraction From Regolith	Large scale in-situ manufacturing and in-situ power systems	Byproduct of Lunar oxygen experiments; TRL 2/3	2018 (demo) 2022 (pilot scale)
In-Situ Surface Manufacture & Repair	Reduced logistics needs, low mission risk, and outpost growth	Terrestrial additive, subtractive, and formative techniques	2010 to 2014 (ISS demos) 2020 (pilot scale)
In-Situ Surface Power Generation & Storage	Lower mission risk, economical outpost growth, and space commercialization	Laboratory production of solar cells on Lunar simulant at <5% efficiency	2013 (commercial demo) 2020 (pilot scale)
Lunar/Mars Surface Cryogenic Fluid Liquefaction, Storage, and Transfer	All ISRU missions that produce oxygen for future use in propulsion systems and EVA/habitat power and life support systems	Laboratory testbeds and oxygen liquefaction and storage under Mars environment simulation	2011 (Mars demo) 2012 (Lunar demo) 2017 (Lunar pilot) 2018 or 2022 (Mars subscale-pilot)

Relationships & Critical Interdependencies of ISRU with Other Roadmaps



	1. High-energy power and propulsion	2. In-space transportation	3. Advanced telescopes and observatories	4.Communication & Navigation	5. Robotic access to planetary surfaces	6. Human planetary landing systems	7. Human health and support systems	8. Human exploration systems and mobility	9. Autonomous systems and robotics	10. Transformational spaceport/range technologies	11. Scientific instruments and sensors	12. *In situ* resource utilization	13. Advanced modeling, simulation, analysis	14. Systems engineering cost/risk analysis	15. Nanotechnology
1. High-energy power and propulsion	🟨											🟥 ISRU (1)			
2. In-space transportation		🟨										🟥 ISRU (2)'!A			
3. Advanced telescopes and observatories			🟨									🟦 ISRU (3)'!A			
4. Communication & Navigation				🟨								🟦 ISRU (4)'!A			
5. Robotic access to planetary surfaces					🟨							🟥 ISRU (5)'!A			
6. Human planetary landing systems						🟨						🟥 ISRU (6)'!A			
7. Human health and support systems							🟨					🟦 ISRU (7)'!A			
8. Human exploration systems and mobility								🟨				🟥 ISRU (8)'!A			
9. Autonomous systems and robotics									🟨			🟥 ISRU (8)'!A			
10. Transformational spaceport/range technologies										🟨		▨			
11. Scientific instruments and sensors											🟨	🟦 ISRU (11)'!			
12. *In situ* resource utilization												🟨	🟦 ISRU (13)'!	🟦 ISRU (14)'!	🟦 ISRU (15)'!
13. Advanced modeling, simulation, analysis													🟨		
14. Systems engineering cost/risk analysis														🟨	
15. Nanotechnology															🟨

Same element	🟨
Critical Relationship (dependent, synergistic, or enabling)	🟥
Moderate Relationship (enhancing, limited impact, or limited synergy)	🟦
No Relationship	▨

Interdependency with Surface Power

Because many ISRU processes are power intensive, the power density of stationary and mobile power systems is important when considering the total benefits and impacts of ISRU on missions and architectures. If ISRU capabilities can be pre-positioned before crew arrive, the same surface power systems can be used later for crew/habitat use, thereby reducing total power infrastructure needs. At the same time, through in-situ production of fuel cell reactants, solar energy generation and storage units, and power management, control, and distribution, ISRU can provide long-term products for a power-rich environment and surface power infrastructure growth. The need date for surface nuclear power is highly linked to the start date for large scale ISRU production.

Interdependency with Propulsion

The production of oxygen for propulsion systems is possible on both the Moon and Mars, however, until more is learned about the hydrogen source and potential resources that may be found at the Lunar poles from Clementine and Lunar Prospector data (hydrogen, water, ammonia or hydrocarbons), it is not known at this time if there is a common in-situ production fuel for both the Moon and Mars. Because Mars is rich in readily available carbon (and potentially water), a number of in-situ produced hydrocarbon fuels are possible. The simplest is methane, however production of methanol, ethylene, benzene/toluene, and short-chain hydrocarbon mixtures have been demonstrated in the laboratory. A risk-benefit study should be performed to assess the benefits-complexity of the fuel choice on both the propulsion system and ISRU plant. In the roadmapping activity, it was assumed that ISRU would provide surface propellant depots and transfer capabilities to lander/ascent and hopper vehicles.

ISRU Products To Other Capabilities				**Capability Products To ISRU**
• H_2 & ^{3}He for NTR & fusion; Ar for electric • Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication • Radiation shields for nuclear reactors • Power cable deployment; in-situ provided power management & distribution	H	High-Energy Power & Propulsion ②	H	• Initial solar & nuclear power to support power-intensive ISRU activities • Mobile/high-density power sources.
• Propellant production and pressurant/purge gases for lander reuse and in-space depots • Aeroshells from Regolith	H	In-Space Transportation ③	H	• ISRU-compatible propulsion • Delivery of ISRU products to sites of exploration and in-space depots
• Shaping crater for collector • In-situ construction and fabrication; foundation design & preparation • Gases for inflatable structures • Raw materials for space based observatory manufacture	M	Advanced Telescopes & Observatories ④	N	
• Raw materials for infrastructure	L	Telecommunications and Navigation ⑤	H	• Mobile equipment navigation. • Fast communication among systems components.
• Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions) • Propellant production for surface hoppers or large sample return missions	H	Robotic Access to Planetary Surfaces ⑥	H	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Landing pads/plume debris shielding • Propellant production/storage/transfer for lander reuse	H	Human Planetary Landing Systems ⑦	H	• Precision landing • Delivery of ISRU capabilities to sites of exploration
• Habitat/shelter fabrication • Gases for inflation & buffer gases • Life support consumable production for backup • Radiation & micro-meteoriod debris shields from in-situ material • Soil & bio-feedstock for plant growth • Materials for in-situ manufacturing	H	Human Health and Support Systems ⑧	L	• Carbon-based waste products as resource for ISRU • Common hardware for possible modularity with ISRU systems
• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 production for EVA • Soil stabilization/dust control • Roadway infrastructure • Engineering properties of regolith	H	Human Exploration Systems & Mobility ⑨	H	• Crew/robotics/rovers to perform ISRU surface activities
• Fuel cell reactants for surface vehicles and aero-bots • New & replacement parts for robotic systems	H	Autonomous Systems & Robotics ⑩	H	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Gases and explosives for science equipment • Increased sample and measurement density for science studies.	L	Scientific Instruments & Sensors ⑫	H	• Resource location & characterization information • Self Calibrating or Extended Calibration Life Sensors

Hi Criticality H Med Criticality M Lo Criticality L No Criticality N

Interdependency with Surface Mobility

Surface mobility assets are critical for the success of ISRU based on the need to excavate and transport large amounts of regolith on the Moon, and potentially on Mars for water extraction. In the roadmapping activity, it was assumed that Surface Mobility assets for ISRU excavation and transport would be provided by the *Human Exploration Systems & Mobility* capability. ISRU would provide its own unique excavation and material handling & transportation units if required. Effort should be made to make crew transport and ISRU surface mobility assets as modular and common as possible to reduce development and launch costs.

Interdependency with Human Support Systems

Even though ISRU will most likely operate autonomously before crew arrival with the minimum of maintenance required, there are critical relationships between ISRU and Human Support Systems. In the roadmapping activity, it was assumed that ISRU would provide backup life support consumable production, storage, and distribution for *Human Health & Support Systems.* It was also assumed that ISRU would provide any manufacturing and construction requiring use or manipulation of local materials, while habitat and surface asset construction through assembly of pre-built units delivered from Earth would be provided by *Human Health & Support Systems*.

Technical & Programmatic Challenges

The Top 10 Technical Challenges below are based on examining the challenges associated with the Key Capabilities & Sub-Capabilities defined in a previous table, and identifying those items that have the biggest potential impact on ISRU plant/element design, performance, maintenance, and/or mission and architecture benefit.

Major Technical Challenges (Top 10 Maximum for Table)
2006-2010
▪ Lunar dust mitigation ▪ Operation in permanently shadowed Lunar crater (40K) ▪ Regolith excavation in harsh/abrasive environments
2010 - 2015
▪ Large scale oxygen extraction from regolith ▪ Autonomous, integrated operation and failure recovery of end-to-end ISRU concepts, including resource excavation, transportation, processing, and storage and distribution of products ▪ Day/night operation (startup/shutdowns) without continuous power ▪ Efficient water extraction processes ▪ Modular, mass-efficient manufacturing and initial construction techniques
2020 and Beyond
▪ Long duration operations with little/no maintenance (300+ sols on Mars) ▪ Habitat and large-scale power system construction techniques

Current State-of-Art (SOA) and Development Activities

As part of the Capability Roadmapping activity, teams were formed to examine the capabilities and technologies of each ISRU Element (see Figure 1) in detail. Below is a top-level summary of this evaluation by ISRU Element. More information can be found in the Appendix: ISRU Element Overview of this report (pg. 30) and in the Power Point presentation to the National Research Council (NRC) presented on April 12, 2005.

Resource Extraction

- Some sub-capabilities have been demonstrated, including scooping of regolith samples on the Moon and Mars, coring of regolith samples on the Moon, and grinding and analysis of rock samples on the Moon and Mars.
- Significant work has been performed on acquiring and separating Mars atmospheric resources. Only preliminary work has been performed on separation/filtration of dust during Mars atmospheric processing and only at very low processing rates.

Material Handling & Transportation

- Extra-terrestrial experience in handling and transporting native materials is very limited for Moon (Apollo samples were manually manipulated for encapsulation and were transported in small containers aboard the Lunar rover vehicle and back to Earth) and Mars (samples were/are robotically manipulated for limited analysis and disposal by Viking, MER, etc.)
- Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge.

Resource Processing

- Lunar ISRU has a 30 year history of laboratory testing, but with little funding for systems level development. The successful demonstration of oxygen production from actual Lunar soils has already been demonstrated using hydrogen reduction of bulk, unprocessed soils as well as ground Lunar basalt [21,22,23]. All of this work has been at the laboratory scale so the Capability Readiness Level (CRL) is a 2 at best. Most of the candidate technologies are in the TRL 3 to 4 range with a research and development degree of difficulty (RD^3) level nominally a II.
- Mars ISRU has had more development over the last decade but the focus has been atmospheric processing. Several prototype systems have been constructed for oxygen and oxygen/methane production, and the TRL of the technology is 4/5, the CRL is 3, and the RD^3 level is I. Laboratory demonstrations have also been performed for other hydrocarbon fuels; methanol, ethylene, benzene/toluene, and short-chain hydrocarbon mixtures (TRL 3/4)
- A significant number of feedstocks can be derived from the Lunar and Martian Regolith. The moon is rich in metals (Fe, Al, Ti, Si) and glasses that can be spun into fibers. Viking data indicates the same metals are available in the Martian regolith suggesting that many of the metal production technologies may be applicable to both the Moon and Mars. Many of the regolith oxygen production technologies leave behind pure metals in their wake. This has been demonstrated at the laboratory scale (TRL 3 or 4). However, none of the laboratory experiments actually separated the pure metals out from the remaining slag. So the CRL for the production of metals is at best a 2.

Surface Manufacturing with In-Situ Resources

- Extensive microgravity materials processing experiments have been done in space in Apollo, Skylab, and Spacelab,
- Paper studies show that 90% manufacturing materials closure can be obtained from Lunar materials and 100% from Mars materials.
- Feasibility efforts for fabrication of photovoltaic cells and arrays out of Lunar derived materials have been performed

Surface Construction

- Site planning: Lunar/Mars topography data sets are partially available, some geophysical characterization is available (Apollo/Mars programs), and Lunar regolith and properties for upper 2 meters is available from the Apollo program
- Structure & Habitat Fabrication: Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, and laboratory tests have been performed on Lunar construction materials (waterless concretes, glass fibers and rods, sintered bricks, etc.)
- Radiation protection: Micro-Meteoroid Debris (MMOD) concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel) and advanced shields were under development during the TransHab project.
- Structure & Site Maintenance: In space maintenance and repair are evolving, self-healing materials are currently being tested , EVA and IVA repairs are regularly performed on the International Space Station, and tile repair tools and materials are being developed as part of return to flight activities for the Space Shuttle
- Landing & Launch Site: Apollo style landings on the Moon showed ejecta occurred but did not threaten the LEM which was ~18 MT. Since the current designs for Lunar landers are a minimum of 28 MT, effects of larger vehicle landing need to be studied and mitigation strategies designed if significant cratering is anticipated so that multiple landings can be accomplished at the same site.

Surface ISRU Product and Consumable Storage and Distribution

- Limited size and capacity cryo-coolers have flown (science instruments)
- Cryogenic fluid storage systems have flown, but for limited durations and not with integrated liquefaction systems
- Automatic and EVA fluid couplings have flown on ISS; Helium II coupling built but not flown

Gaps in ISRU Development

Most ISRU technology and system development to date has focused on oxygen production from Lunar regolith, construction feedstock production (cement and bricks) from Lunar regolith, and oxygen and fuel production from Mars atmospheric carbon dioxide. Funding for ISRU has been minimal for the last 5 years. Therefore, there are numerous gaps in ISRU development. The list below covers the highest priority gaps that need to be addressed before ISRU can be utilized effectively in future human missions.

- Dust mitigation techniques to prevent hardware wear and life issues
- Reduced-gravity effects on solid material handling, processing, manufacturing, and construction
- Definition of Moon and Mars water and resource extraction, handling, & transportation technologies and capabilities for the Moon and Mars environment
- Development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment.
- Processes to produce oxygen and manufacturing and construction feedstock from regolith
- Tele-operation and/or automation of robotic excavation, transportation, and construction processes
- Dust insensitive fluid couplings and leak detection in open vacuum or low atmospheric environments
- Mass, volume, and power efficient cryogenic storage and distribution systems
- Resource prospecting instruments and ISRU control sensors
- Modular, highly flexible, and compact manufacturing techniques for in-situ fabrication & repair
- Development of power generation, management, and distribution from in-situ resources and feedstock

Risks for Incorporation of ISRU into Missions

There are two primary risks associated with incorporation of ISRU into mission and architecture plans: Resource Risks and Technical Risks.

With respect to Resource Risks, there are three primary concerns: the resource of interest is not available at all, the resource of interest is not available at the landing site, and the resource of interest is at the landing site but not in the form, location, or purity expected. For these risks, some level of resource assessment and prospecting is required before human missions are performed using ISRU. At this time, it is not clear whether a robotic mission will always have to be flown to future sites of human exploration or if a limited number of ‘ground truth’ missions can be used to validate orbital data measurements to levels of acceptable risk.

With respect to Technical Risks, there are several concerns irrespective of the ISRU concept chosen. For example, any ISRU process that excavates and processes regolith will have uncertainties associated with the efficiency/performance of the processes and the amount of regolith required to meet production goals. Also, sealing of regolith processing systems, especially at elevated temperatures and under vacuum conditions will be difficult. Until ISRU demonstrations are flown, the unknowns associated with maintenance and repair, system reliability, robustness, and effects of Lunar and Mars environmental conditions will not be known. Even though extensive testing in ground laboratory, field, and environmental simulation chambers is planned, the combined impacts of these risks can not be assessed without flight demonstrations.

Facilities Unique to ISRU Development & Certification

4. *What are the critical facilities or other physical infrastructure needed to execute this roadmap?*

Conditions on the moon include high vacuum, large temperature variations during the lunar day, low temperatures during the lunar night and at the poles, reduced gravity, and highly abrasive dirt environment. 20 percent (by mass) of the Apollo returned samples were less than 20 microns. While conditions on Mars do not include the high vacuum, they do include wide temperature variations dependent on day/night and winter/summer cycles and on latitude. The Mars atmosphere also introduces dust storms at up to 95 m/s (300 km/hr). The table below lists the relevant conditions on the surface of the moon and Mars.

Test Simulation Condition	Pressure (torr)	Temperature (K)	Wind (km/hr)	Gravity (Earth = 1)
Lunar Day	10^{-10}	255 – 390	N/A	1/6
Lunar Night	10^{-11}	120	N/A	1/6
Lunar Poles	10^{-11}	40	N/A	1/6
Mars*	2.25 – 7.5	145 – 240	300	0.38

In addition to these physical conditions, most of the ISRU capabilities will require simulants in the test chambers to demonstrate operation in a relevant environment. While many tests will only require dust simulant to demonstrate that the equipment can operate in the abrasive environment, the excavation, material handling and transport, and surface construction capabilities will require layers of regolith simulant. For excavation tests and development, the regolith will need to be layered up to 2 meters deep with the correct stratification as found on the lunar surface.

In evaluating the ability of existing facilities to properly simulate the lunar surface environment, a note needs to be made concerning the very low pressures on the moon. The best pressure that facilities larger than approximately 1 ft^3 can obtain is between 10^{-6} and 10^{-8} torr. However, before claiming that hard vacuum simulation is therefore a critical gap, we must evaluate the physical processes that are affected by pressure and determine at what level of vacuum do changes in these physical processes stop occurring. To date, the following five processes have been considered:

- Electrical: in a rough vacuum, an electrical spark has a tendency to arc to a wall 20 feet away instead of a few millimeters away due to the Paschen curve breakdown. This is not an issue beyond approximately 10^{-3} torr.
- Heat Transfer: both convection and thermal conductivity (through a gas phase) are functions of gas pressure. Sources indicate that beyond approximately 10^{-4} torr these are both essentially zero.
- Self-Welding: Two flat, bare metal surfaces have a tendency to stick when brought together, a process referred to as self-welding, cold-welding, or friction welding. Since metal surfaces in an atmosphere have an oxide coating which is quickly reformed when stripped away due to rubbing or scraping (and are therefore not ‘bare’ metal), self-welding is not a common problem. However, in a vacuum there will be no reforming of the oxide layer when machinery parts rub together. Unfortunately there are many variables that would affect the process of self-welding (e.g. the load that two parts are placed under) and it is difficult to predict what vacuum level is good enough to test this issue.
- Bulk Materials: The angle of repose, or heaping behavior, of granular media is affected by the gas pressure. Gas molecules can fill the pores of the grains or even form a coating of molecules on the grain surfaces. Limited two-dimensional tests performed showed that the heap height increased as pressure was lowered below 760 torr (1 atm) until about 100 torr where the height then plunged.

Since no data on this phenomena exists below 1 torr, it is difficult to predict at what pressure the behavior levels out. Experts predict insignificant changes by 10^{-3} or 10^{-4} torr.

- Seals: The effect of a hard vacuum on seals was also considered, since sealing in an abrasive environment will be a critical technical challenge. However, since seals respond to a delta pressure, and the pressure on the inside of the seal will be 1 atm or higher, then the seal will behave the same in a coarse vacuum or hard vacuum since the delta pressure is basically the same.

Based on the above physical processes and their affects at low pressures, it appears that existing facilities that can achieve 10^{-6} to 10^{-8} torr are sufficient to demonstrate operation in a relevant environment for ISRU technologies and capabilities.

5. Where do the critical facilities or other physical infrastructure exist to execute the roadmap (within NASA, Industry, Academia, Other Government)?

The majority of facilities that meet the requirements of lunar and Mars surface simulation exist at NASA or other government sites. One critical issue is whether or not the facility is tolerant (and willing) of introducing simulants (aka dirt) into the vacuum chamber. In general, vacuum chambers that use cryo pumps will be tolerant of dirt, and vacuum chambers that use oil diffusion pumps will not be tolerant.

An attempt was made to survey existing facilities to determine best matches for the requirements listed above. NASA, DoD, and some industry and academia were contacted. Not all responded. Below is a list of some of the applicable facilities identified so far.

- Space Power Facility (SPF), NASA GRC's Plum Brook Station. This is the world's largest vacuum facility at 30 m diameter by 33.5 m tall. It has a vacuum pressure of 10^{-6} torr, and a controllable temperature range of 80 K – 390 K. Its cryo pumps are tolerant of dirt, and the facility has already performed tests with simulated Martian rocks and dust for the Mars Exploration Rover (MER) airbag drop tests.
- Space Environment Simulation (SES), NASA GSFC. A very large vacuum chamber at 8 by 12 meters, and one of only 4 facilities found with a controllable temperature that can simulate the lunar poles. The chamber cryo pumps should be tolerant to dirt. (Note, the GSFC web site for this facility lists the temperature range as only 93K and 143 K – 373 K, but may not have been updated since the helium refrigerator was recently installed.)
- K-Site, NASA GRC. A 7.6 meter chamber with 4 meter diameter cold shroud with excellent pressure (5 x 10^{-8} torr) and lunar pole temperatures (20K – 394K). However, its oil diffusion pump would require a filtration system (minor mod) to enable testing with simulants. This facility has a shaker system that allows for vibration and shock testing under thermal-vacuum conditions.
- Chamber A and Chamber B, NASA JSC. Both have cryo pumps tolerant of dirt, a pressure capability of 10^{-6} torr, and low temperature (77K). Chamber A is 15 by 27.5 meters and Chamber B is 7.6 by 7.6 meters.
- 20' (6 m) Subsystem Altitude, NASA JSC. With a pressure of 10^{-2} torr and a temperature range of 145 K – 300 K, this facility has already performed tests with a mixture of gases to simulate the Mars atmosphere.
- Mars Wind Tunnel, NASA Ames. 16 m long with a 1.2 m square test section, this wind tunnel has been used to simulate dust storms on Mars at simulated pressures. It does not have any temperature simulation capability.
- Zero-G, NASA GRC. The world's biggest drop tower, it can achieve 10^{-5} gravity level for 5.2 seconds. Simulants and low pressures can both be achieved inside sealed test chambers.

- C-9 Aircraft, NASA. By flying parabolic trajectories, this aircraft can achieve various gravity levels: 20 seconds of micro-g, 30 seconds of lunar-g, and 40 seconds of Mars-g per parabola. The total payload bay is 15 m long with a 2.5 by 2 m cross section.
- DoD AEDC. The Mark I (13 by 25 m) and 10V (3 by 9 m) facilities both have vacuum capabilities in the 10^{-7} torr level. The 10V lists a lunar polar temperature capability, but it has an extremely high cleanliness rating (100), and it is unlikely that they would be willing to introduce simulants into this chamber. The Mark I lists a temperature range of 77K – 373K, but its high cleanliness rating of 1K also implies an unwillingness to introduce simulants.

6. Are there any special physical infrastructure planning considerations that the roadmapping team thinks should be highlighted?

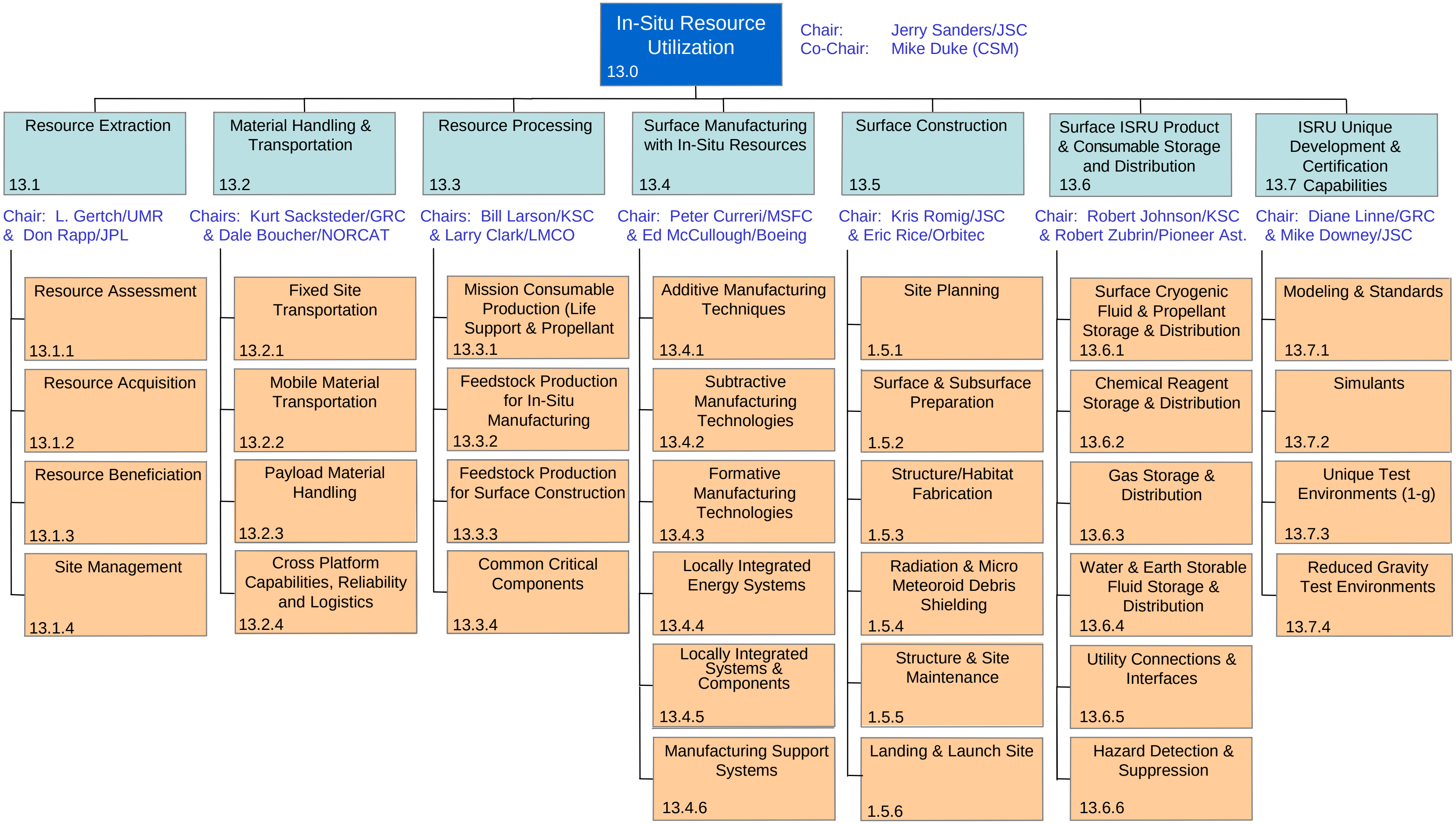
Vacuum test chambers that introduce dust and regolith simulants may never be able to regain a high cleanliness rating required for other capability development such as advanced telescopes and observatories and scientific instruments and sensors. The challenge will be to convince certain facilities to become “dirty” facilities with sufficient long-term test possibilities that these “dirty” facilities will not be hurt by the potential loss of test programs that require “clean” facilities.

In addition to vacuum chambers that are tolerant (and willing) of using simulants on a large scale, remote equipment to handle, distribute, and charge simulants within the evacuated vacuum chamber is required. It may be necessary to create and maintain simulants in a vacuum environment to avoid saturating with terrestrial constituents.

There is no capability for long-term simulation of reduced gravity, and it is unlikely that one will be built unless a free-flying centrifuge or tethered facility is funded. Currently we must send robotic demos to prove out long-duration reduced gravity capability, and the opportunities for these flights are limited.

Finally, there is no medium-to-large scale integrated test capability that can duplicate the thermal, vacuum, dust, *and* gravity environment simultaneously.

Fig 1: In-Situ Resource Utilization (ISRU) Capabilities Breakdown Structure (CBS)



- In-Situ Resource Utilization 13.0 — Chair: Jerry Sanders/JSC; Co-Chair: Mike Duke (CSM)
  - Resource Extraction 13.1 — Chair: L. Gertch/UMR & Don Rapp/JPL
    - Resource Assessment 13.1.1
    - Resource Acquisition 13.1.2
    - Resource Beneficiation 13.1.3
    - Site Management 13.1.4
  - Material Handling & Transportation 13.2 — Chairs: Kurt Sacksteder/GRC & Dale Boucher/NORCAT
    - Fixed Site Transportation 13.2.1
    - Mobile Material Transportation 13.2.2
    - Payload Material Handling 13.2.3
    - Cross Platform Capabilities, Reliability and Logistics 13.2.4
  - Resource Processing 13.3 — Chairs: Bill Larson/KSC & Larry Clark/LMCO
    - Mission Consumable Production (Life Support & Propellant 13.3.1
    - Feedstock Production for In-Situ Manufacturing 13.3.2
    - Feedstock Production for Surface Construction 13.3.3
    - Common Critical Components 13.3.4
  - Surface Manufacturing with In-Situ Resources 13.4 — Chair: Peter Curreri/MSFC & Ed McCullough/Boeing
    - Additive Manufacturing Techniques 13.4.1
    - Subtractive Manufacturing Technologies 13.4.2
    - Formative Manufacturing Technologies 13.4.3
    - Locally Integrated Energy Systems 13.4.4
    - Locally Integrated Systems & Components 13.4.5
    - Manufacturing Support Systems 13.4.6
  - Surface Construction 13.5 — Chair: Kris Romig/JSC & Eric Rice/Orbitec
    - Site Planning 1.5.1
    - Surface & Subsurface Preparation 1.5.2
    - Structure/Habitat Fabrication 1.5.3
    - Radiation & Micro Meteoroid Debris Shielding 1.5.4
    - Structure & Site Maintenance 1.5.5
    - Landing & Launch Site 1.5.6
  - Surface ISRU Product & Consumable Storage and Distribution 13.6 — Chair: Robert Johnson/KSC & Robert Zubrin/Pioneer Ast.
    - Surface Cryogenic Fluid & Propellant Storage & Distribution 13.6.1
    - Chemical Reagent Storage & Distribution 13.6.2
    - Gas Storage & Distribution 13.6.3
    - Water & Earth Storable Fluid Storage & Distribution 13.6.4
    - Utility Connections & Interfaces 13.6.5
    - Hazard Detection & Suppression 13.6.6
  - ISRU Unique Development & Certification 13.7 Capabilities — Chair: Diane Linne/GRC & Mike Downey/JSC
    - Modeling & Standards 13.7.1
    - Simulants 13.7.2
    - Unique Test Environments (1-g) 13.7.3
    - Reduced Gravity Test Environments 13.7.4

Appendix: ISRU Element Overview

To evaluate the benefits, state-of-the-art, gaps, risks, and challenges of ISRU concepts, seven ISRU capability elements were defined and examined: (i) resource extraction, (ii) material handling and transport, (iii) resource processing, (iv) surface manufacturing with in-situ resources, (v) surface construction, (vi) surface ISRU product and consumable storage and distribution, and (vii) ISRU unique development and certification capabilities. (Figure 1. ISRU Capability Breakdown Structure). This section will provide a brief description of each element, their benefits, state-of-the-art, and challenges, gaps and risks.

Resource Extraction

- *Element Description*: Resource Extraction provides raw materials – gas, liquid, and solid – from the local environment by removing them, concentrating them, and preparing them for further processing, manufacturing, or direct use. It is the first step in "living off the land" in a sustainable manner.

Resource Extraction consists of four parts. Resource Assessment determines what is available, where it is, what form it is in, and how it can best be extracted. This is followed by Resource Acquisition, which separates and removes the target raw material from its original location. Then Resource Beneficiation converts the raw material into a form suitable for direct use, manufacturing, or further processing. Site Management comprises the supplemental capabilities needed for safe, effective operation of all aspects of Resource Extraction.

The primary link to other ISRU elements is through Material Handling and Transport, which removes the products of Resource Extraction – feedstocks ready for use (to Surface Construction), manufacturing (to Surface Manufacturing), or further processing (to Resource Processing) – and brings fuel and supplies from Surface Storage, Surface Manufacturing, and cargo landing sites to Resource Extraction sites.

Resource Extraction requires power, which could be supplied initially by the High Energy Power capability and later by ISRU-generated power. Other critical needs would be provided by the Telecommunications and Navigation, Robotic Access to Planetary Surfaces, Human Exploration Systems and Mobility, Autonomous Systems and Robotics, and Scientific Instruments and Sensors capabilities. Resource Extraction activities would in turn provide feedback to the Advanced Modeling, Simulation, and Analysis; Systems Engineering and Cost/Risk Analysis; and Nanotechnology/Advanced Concepts capabilities.

- *Benefits of Resource Extraction*: The primary benefit of Resource Extraction is its reason for being: To provide the raw materials to begin ISRU. This includes feedstocks for production of propellants and life support gasses, safe spaces for humans and equipment (pit/trench excavation and bulk radiation shielding production), and eventually fuel for power generation.

- *State of the Art & Currently Funded Activities*: Technologies for extracting mineral resources have been under development for at least 50,000 years and possibly 1,000,000 years[u]. They have been repeatedly successful at production rates from a few liters/day to 200,000+ tonnes/day in a broad array of environments from 4,600 m elevation to 3,800 m depth in Earth's crust; in locations accessible only when the ground freezes, when it thaws, or when artificially stabilized; from the centers of cities to the remote tundra; and within and beneath rivers, lakes, and oceans. Modern mining and quarrying routinely rely on automated drilling/boring, fragmentation, excavation, and transportation of rock and soil, both underground and on the surface. These are extremely mature technologies that have been broken down and studied in their most basic forms for several hundred years. They can be translated to lunar and Martian conditions with a comprehensive series of small but well-focused research programs.

Several NASA-funded projects are presently addressing aspects of Resource Extraction:

- Modular Regolith Characterization Instrument Suite (USACE Cold Regions Research and Engineering Lab, Honeybee Robotics, Applied Research Assoc., University of Arizona, Los Alamos National Lab, several NASA Centers) will develop instruments to analyze soil and rock on the moon and Mars with an eye toward mining and construction there.
- Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) (Northern Center for Advanced Technology, Colorado School of Mines, Lockheed Martin, Boeing, Orbitec, several NASA Centers) consists of five experiments dealing with assessment, excavation, and processing of regolith from permanently shadowed lunar craters to release volatiles and produce oxygen.
- ISRU for Human Exploration - Propellant Production for the Moon and Beyond (Lockheed Martin)
- SBIR (Phase I or II):
  - Low-energy Planetary Excavator (LPE) (Orbitec) is developing a concept for a single surface excavator capable of dealing with the different material properties expected on the Moon and Mars, from poorly sorted to well-sorted regolith and ice-regolith mixtures.
  - Sample Acquisition for Materials in Planetary Exploration (SAMPLE) (Orbitec) is developing an autonomous lunar surface/subsurface sampler/processor that will encapsulate samples to minimize vibration effects and volatiles loss.
  - Collection and Purification of Lunar Propellant Resources (Technology Applications Inc.) is developing innovative thermal management techniques to collect and purify volatile propellant materials extracted from moderate to high vacuum environments.
  - Autonomous Tethered Corer for Deep Drilling (UTD Inc.) is producing a prototype self-propelled percussive mole for accessing the Martian subsurface (below several meters).

▪ *Challenges, Gaps and Risks*: The first critical need is for detailed specifications of the products required from the Resource Extraction element, including feedstocks and construction materials. Until this gap has been filled, target planetary materials cannot be identified sufficiently for mission planning.

Once the target materials are known, Resource Assessment technologies must be improved to obtain information in the third planetary dimension (*i.e.*, the subsurface). Orbital observation technologies are well-developed, but penetrate soil and rock to only a few meters at insufficient resolution (1-10 cm vertical and 1-10 m lateral resolution is needed). Orbital surveys must therefore be supplemented with *in situ* geophysical surveys and systematic collection/evaluation of physical samples. Of these, physical sample collecting is the most challenging. Fault recovery (*e.g.*, stuck bit) will be a difficult aspect.

The greatest overall challenge is to effectively modify terrestrially mature technologies for acquiring and beneficiating regolith. The most efficient approach is to keep the fundamental unit operations always in mind – fragmentation, excavation, and separation are especially important for regolith mining – and make minimal changes only where necessary. The needed capabilities are common to all environments; it is only the technologies needed to achieve them that vary. Simple machines and systems are at once more robust, more flexible, and easier to maintain than complex ones, but more challenging to develop.

Other necessary research areas include:

- Adapting *in situ* geophysical surveying technologies (aerial, surface-based, in-hole, and combined approaches) for lunar and Martian use. Many approaches have reached terrestrial maturity, and an even wider variety are in various stages of development.
- Conceptual models of the formation and segregation of natural materials in extra-terrestrial venues. The physical, chemical, and thermal processes that control resource deposit formation are universal, but their implementations are very different among different solar system bodies.
- The behavior of granular materials on the Moon and Mars. As roadway, working floor, and raw materials source, understanding and predicting regolith behavior is vitally important to the success of Resource Extraction and thus of ISRU. Scaling issues are nonlinear and nontrivial.

The risks inherent from insufficient preparation are low system efficiency, high energy needs, high human intervention, and low productivity. Industrially unacceptable efficiencies are expected in early stages of exploration, but must not be so low that mission objectives are compromised.

Material Handling & Transportation

- *Element Description.* The Material Handling and Transportation aspects of ISRU include capabilities for handling and moving resource materials in the challenging environments of space, including wide variations in ambient temperature, pressure and gravity. The capabilities include material handling within and between various ISRU devices and the transportation of materials short distances within a discrete operations site or over longer distances to support human or robotic operations not directly tied to ISRU. The materials include raw and beneficiated resources (e.g. regolith, atmosphere, etc.), and intermediate and final product materials (e.g. cryogenic propellants, I-beams, etc.) that may be solid, liquid, vapor or multi-phase.

Resource material such as raw or product fluids but also regolith holding volatile components may require environmentally-controlled containment. Granular media, multi-phase fluids and reacting system behavior is affected by the local gravity level. Short distance movement of materials includes stationary devices such as augers, conveyors, cranes, plumbing, pumps, etc. Long distance movement of materials includes surface vehicles such as wheeled, tracked or rail-based; and flight vehicles including aircraft or rocket propelled hoppers; plus the roads or other infrastructure needed for them. Cross platform capabilities include power and fuel handling; mechanisms and container seals; sensors and artificial intelligence; and strategies for logistics and system reliability.

- *Benefits*. Material handling and transportation capabilities in ISRU systems will enable the manipulation of wide-ranging quantities of ISRU materials independent of the specific technology chosen for resource collection, processing or storage. Additionally, this capability enables the separate and independent placement of desirable sites for human or robotic operations and sites for resource collection, processing, and storage of in-situ resources.

- *State of the Art and Current Activities.* Extra-terrestrial experience in handling and transporting native materials is very limited. Apollo samples were manually manipulated for encapsulation and return to Earth. Small Apollo samples were transported in small containers aboard the Lunar rover vehicles. Considerable problems were encountered by the Apollo astronauts related to regolith dust resulting in equipment degradation and compromised material containment. Martian surface samples were and are robotically manipulated for limited analysis and disposal, including the Viking, Mars Odyssey, and the Mars Exploration Rovers.

Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge. After years of study of the Apollo returned samples, the science community does not claim the ability to predict the material handling behavior of significant quantities of lunar regolith in the lunar environment. Terrestrial handling of granular media is largely empirical and may not be scalable – reduced gravity, temperature and pressure and abrasive lunar regolith will amplify the uncertainties. Space- based technologies for handling materials that would be affected by the gravity level, including multi-phase and non-isothermal fluids, have been largely avoided to enable pre-flight ground testing. Gravitationally influenced technologies will be essential to realistic ISRU operations and might be optimized for the particular ambient gravity level. The operational approach to power consumption, reliability, logistics, etc. requires blending terrestrial experience with space realities. Generally, since the lessons of the Apollo, Mars science missions and the NASA Microgravity program have not yet been applied to the technical challenges of the material handling in the lunar and martian environment, the TRL level of the component technologies is at three or less.

Very limited relevant work is ongoing to establish capabilities for material handling and transportation for ISRU systems. The NASA Exploration Systems Mission Directorate is currently supporting ISRU and related technology development efforts leading to concepts for ISRU demonstrations, primarily on the moon. The RESOLVE and PILOT projects are developing approaches to collect lunar regolith and extract volatile components and oxygen, requiring manipulation of regolith samples between 0.1 to 100 kg in ambient temperatures ranging from 50 – 400 K ambient temperatures, hard vacuum and 1/6th times Earth gravity. A Dust mitigation program is developing technologies to prevent and remove the accumulation of dust from regolith and will contribute material handling techniques for very small particles. Other ISRU related projects do not address material handling issues. Finally, a variety of small studies supported by the former Physical Sciences Division, now part of ESMD, are providing characterizations of reacting systems, multi-phase flows, and granular media behavior in variable gravity environments. No current efforts consider specific technologies to transport materials over any distance.

- *Challenges, Gaps and Risks*. Developing effective and reliable capabilities for handling and transporting materials to support ISRU systems is challenged by the perception that relatively straightforward engineering adaptations of extensive terrestrial experience will be sufficient. Due to the physical and chemical properties of lunar and planetary soils that are unique and difficult to reproduce, the wide variations in the ambient temperature and pressure, the low gravity environment and imperatives for minimum system mass and high reliability, it is instead more likely that these capabilities will require significant innovation to implement.

Since material handling in ISRU systems will undoubtedly include gravitational effects, the ability to directly verify performance before mission implementation will be an ongoing challenge. Additionally, since little space flight technology has been developed to utilize varying gravity levels, much of the needed technology will have little flight heritage on which to build. It is important to note that attempting to predict partial-gravity behavior of ISRU systems by simply interpolating between normal Earth gravity behavior and microgravity behavior observed on the Space Station could be entirely misleading. Reducing the ambient gravity level suppresses physical and chemical mechanisms directly affected by gravity, but other mechanisms, not important in Earth gravity, arise to dominate behavior at low gravity. It may be that the greatest risk to the development of operational capabilities for material handling and transportation lies in the lack of testing capability in the partial gravity environment in which the system must eventually function.

Specific technology gaps in the handling and transportation of materials in ISRU systems include: 1) adequate characterization of the native material properties leading to realistic earth derived simulants for process development and demonstration, 2) technologies for handling and movement of quantities of lunar or martian regolith and solid product materials ranging from samples on the order of grams to operational quantities on the order of 10s or 100s of kilograms, where these technologies are developed with equipment weight savings, material properties, low gravity, and high reliability and system life as prime parameters; 3) reliable fluid handling systems for partial-gravity environments that involve heat and mass transfer processes, and are multiphase, reacting or otherwise non-isothermal in nature; and 4) a variety of special technology problems including reliable seals, valves, containers, mechanisms etc. that are challenged by low temperatures, pressure variations from very hard vacuum to high pressure, abrasive, intrusive and electrostatically charged dust and partial gravity.

Resource Processing

- *Element Description:* Resource processing is the element of In-Situ Resource Utilization that deals with the conversion of raw materials found at an exploration destination into usable products. The types of products produced fall into three classes, Mission Consumables, Feedstock for Manufacturing and Feedstock for Construction. Mission Consumables encompasses a variety of fuels for propulsion, oxygen for propulsion and life support, the purification of water, buffer gasses for life support and science and the production of fertilizer for plant growth. Feedstock production will provide the processed materials needed to manufacture spare parts and conduct local construction activities.

The Resource Processing Element will have interfaces with several other ISRU Elements. It will receive raw materials from either the Resource Extraction or Material Transportation Elements. Products produced by Resource Processing will be go back to the Material Transportation Element in the case of solids (e.g. metals, ceramics). Liquids and gasses will be delivered to the Storage and Distribution Element.

- *Benefits of Resource Processing*: Mission Consumables are significant mass drivers for exploration missions. The largest mass fraction of any spacecraft that has to ascend from the surface of a planetary body is the propellant and oxidizer. NASA's Design Reference Mission 3.0 Addendum calls for 39,000 kg of propellant to return the Astronauts to Mars orbit. That exceeds the capability of any launch vehicle currently in production[24,25]. Even if we still had a Saturn V available, the Mars ascent propellant would consume 43% of its payload capability. So it becomes very clear that propellant manufacturing at the destination is a key product of the Resource Processing Element. Depending on the technology chosen for the Trans Mars Injection stage the mass savings from LEO to the Mars surface varies from 3.5:1 to 5:1. The table below summarizes the mass savings achieved in a number of Mars mission studies using a reasonably conservative 4:1 savings ratio.

Mission Name	**Propellant Produced (mt)**	**ISRU Plant Mass (mt)**	**Mass Seed Hydrogen (mt)**	**Mass To Surface Saved (mt)**	**Mass In LEO Saved (4:1) (mt)**
Bimodal NTR [26]	39.5	2.4	4.1	33.0	132.1
DRM 3 [27]	39.0	3.9	5.4	29.7	118.8
DRM 3 [28] (cache + rover fuel) 6 types	101.4	3.9-10.8	4.4-10.4	42.8-60.1	171.0-240.5
Mars Direct [29]	108	*~6*	6	96	384

It is also important that the Resource Processing Element be able to produce significant quantities of Oxygen, Water and Buffer Gases for Life Support applications. While most mission architectures use some form of closed loop life support, the system efficiencies are unlikely to reach 100%. Should a portion of the regenerative life support system fail, it will be critically important to have the capability of producing additional life support consumable caches. Looking into the future, once we establish permanent settlements on the surface of other planetary bodies, it will be necessary to generate fertilizer to support food production.

Timely logistic resupply becomes impossible once we move beyond the near-earth neighborhood and on to Mars. The 26 month time between available launch windows means that Human Mars Missions will have to be able to have an in situ repair capability. It would be prohibitively expensive to carry spare parts for every component in the exploration architecture so the ability to manufacture parts will be critical. The first step to establishing this ability is developing the capability to produce feedstocks that can be used by the Manufacturing Element of ISRU.

A benefit of Resource Processing that extends beyond the immediate NASA mission is the possibility of Space Commercialization. For any commercial entity to exist it must have a product that someone wants. Propellant production may be the product that finally stimulates a commercial industry for space. As mentioned previously, there is a tremendous penalty when we try to lift propellant mass out of earth's deep gravity well into LEO. If propellants could be produced on the Moon an infrastructure could grow to allow the refueling of satellites in GEO or even LEO. An enterprise of this magnitude would never be undertaken by industry alone, there is too much risk. However, if NASA developed the initial infrastructure on the Moon for it's own purposes, then industry may move in to take it over and expand it. As an example, NASA paid for the first large scale hydrogen production facility in the country in the early 1960's to support the Apollo Program. The plant was built on the outskirts of New Orleans to be close to the engine development testing at what is now NASA's Stennis Space Center. The plant was run by, and eventually turned over to Air Products, who doubled the capacity of the plant in the 70's and is now one of the leading suppliers of cryogenic fluids in the country. During the early days, the government was by far the largest user of liquid hydrogen in the country and therefore needed to make the necessary infrastructure investment to ensure mission success. Today the cryogenics industry has grown such that the roles are reversed; the government is now just a small Air Products customer.

- *State of the Art & Currently Funded Activities*: It may come as a surprise, but a number of resource processing technologies have been under development for hundreds of years. For example, the Sabatier reaction, which is used to produce Methane from the Mars atmosphere, is named for a French Chemist Paul Sabatier, who invented the process in the 1890's. Distillation, which can be used for water and CO_2 purification has been around since the 1700's when Ben Franklin developed a system for the British Navy. So the state of the art of resource processing technologies is not limited by knowledge of the necessary chemistries, but rather the system level development necessary to implement it for the exploration mission.

Lunar oxygen production chemistries have a 30 year history of laboratory testing. Our Roadmapping effort identified many technical approaches to producing oxygen from the regolith of the moon. All of this work has been at the laboratory scale so it Capability Readiness Level (CRL) is a 2 at best. Most of the candidate technologies are in the TRL 3 to 4 range with a research and development degree of difficulty (RD^3) level nominally a II.

Lunar propellant production is a tougher area to characterize. There is evidence of elevated hydrogen concentrations at both poles, but the chemical form of that hydrogen and its accessibility are unknown at this time. Hydrogen and Carbon are available in PPM levels anywhere on the surface of the moon (solar wind implantation) and they are present in concentrations appropriate for the production of methane, a reasonably efficient rocket fuel[30]. The readiness levels for the chemical processes necessary to produce fuel are fairly high (9 for water electrolysis, 5 for Sabatier Reactor) with an RD^3 level of I. However, the capability readiness level is very low (1) when extraction of hydrogen from the regolith is factored into the equation.

A significant number of feedstocks can be derived from the Lunar and Martian Regolith. The moon is rich is metals (Fe, Al, Ti, Si) and glasses that can be spun into fibers. Viking data indicates the same metals are available in the Martian regolith. This suggests that many of the metal production technologies may be applicable to both the Moon and Mars. Many of the regolith oxygen production technologies leave behind pure metals in their wake. This has been demonstrated at the laboratory scale places it at TRL 3 or 4. However, none of the laboratory experiments actually separated the pure metals out from the remaining slag. So the CRL for the production of metals is a best a 2. Metals refinement is a well establish industry, however, performing this in an extraterrestrial environment will be a challenge. Therefore the RD^3 level for advancing this to a usable state warrants a III. The slag left over from metals an oxygen production can prove useful as a feedstock for the production of bricks or construction blocks.

Mars oxygen and fuel production has enjoyed a greater amount of attention over the last 10 years. The development focus has primarily been on atmospheric processing technologies. The Sabatier reactor is the primary fuel (methane) production technology. Several prototype systems have been constructed and the TRL of the technology is 5, it's CRL is 3 and an RD^3 level of I. Oxygen is also generated through the electrolysis of water, a byproduct of the Sabatier reaction, but it is produced a quantity that is insufficient for efficient propulsion. The additional oxygen can be produced by a number of technologies, Solid Oxide Electrolysis, Reverse Water Gas Shift (RWGS) reaction and Cold Plasma CO_2 Dissociation. The first two listed have had extensive prototyping and testing completed. Solid Oxide Electrolysis (SOE) was slated to fly as an ISRU demonstration on the Mars 2001 lander, but the mission was canceled. Readiness levels among these three technologies varies with SOE being the most advanced at TRL 6, RWGS at 4 and Cold Plasma at 3. RD^3 is a III for SOE and II for the other two technologies. Overall, the CRL is estimated to be 3.

Currently NASA is funding four projects that address resource processing.

- Microchannel In Situ Propellant Production System: Battelle Memorial Institute is working on a propellant and oxidizer production system using microchannel reactors. The system integrates the exothermic Sabatier Reactor with the endothermic Reverse Water Gas Shift Reactor. The result will be Methane and Oxygen production in a ratio suitable for rocket propulsion.
- ILMENOX: British Titanium has been funded to develop this Lunar oxygen production technology. The process focuses on removing all of the oxygen from the mineral ilmenite ($FeTiO_3$). Ilmenite makes up 15 to 20% of some of the Lunar mare basalts. Previous processes for ilmenite reduction only extract 1/3 of the oxygen.
- Integrated In-Situ Resource Utilization for Human Exploration – Propellant Production for the Moon and Beyond: Lockheed Martin Astronautics proposes to develop an end to end Lunar oxygen production process. The project will develop a robotic excavator, oxygen production system and the oxygen produced will be liquefied and stored.
- RESOLVE: Development of a Regolith Extraction and Resource Separation & Characterization Experiment for the 2009/2010 Lunar Lander: A NASA JSC led project with support from KSC, GRC & JPL. The experiment's primary goals are to determine the concentration and form of Lunar polar hydrogen and capture it, and to demonstrate the production of oxygen from the Lunar regolith. The experiment will also characterize the soil mechanics and the fine grain characteristics of the Lunar polar soil.

- *Challenges, Gaps and Risks*:

Surface Manufacturing with In-Situ Resources [31,32,33]

- *Element Description:* Surface Manufacturing with In Situ Resources is a set of capabilities that enable repair, production of parts and integrated systems on the Moon and beyond using in situ resources. The capability read map (Element 13.4 of the ISRU Capability Road Map) is organized into six subcategories: Additive Manufacturing which includes processes such free form "rapid prototyping" from powders, composite formation, and chemical vapor deposition; Subtractive Manufacturing which includes formation by machine tools, e-beam and Lasers; Formative Manufacturing which includes casting, extrusion, sintering and combustion synthesis; Locally Integrated Energy Systems including the manufacturing of photovoltaic arrays, solar concentrators and beaming and storing of in situ derived power; Locally Integrated Systems where parts of the other elements are joined into working systems, and Manufacturing Support Systems which entails the methods of measuring and evaluating the fitness of in situ manufactured products. It us understood that the surface manufacturing element will be integrated into the other elements of the ISRU Capability. For example feedstock will be delivered from the Resource Processing Element with the support of the Transportation Element. Conversely, Surface Manufacturing produces space parts and repair services for all surface operations. Surface Manufacturing will deliver expandable power for the in situ resource extraction, processing, surface construction, manufacturing and the external exploration community.

- *Benefits of Manufacturing with in Situ Resources:* First, the capability provides In Situ Repair and Spare Parts Manufacturing. This capability enables safe and timely recovery from system failures using in situ versatile manufacturing techniques (with design files from terrestrial design centers) without long and expensive logistics from Earth. In the long term, this capability enables the development of safe, self-sufficient, self-sustaining systems on the Moon and beyond. Second, In Situ Manufacturing with In Situ Resources provides an on site industrial plant capability that can manufacture critical products with masses orders of magnitude greater than the mass of the manufacturing facility. This capability eventually enables the production of the second and future generation industrial almost entirely (80-95% on the Moon and near 100% on Mars) from in situ resources. Third, Surface Manufacturing of In Situ Energy Systems enables the in situ development on the Moon and beyond of Energy Systems capable being expanded for decreased cost as production is increased. Studies predict that, for example, a 1 MW solar cell system can be produced on the Moon with in Situ resources for 1/10th the launch mass as a non in situ system[7]. The culmination of this capability is to provide an affordable and sustainable energy-rich environment in Space. All of these capabilities combined with support of the other ISRU elements enables credible large scale Space Commercialization and Development and low cost Human Exploration.

- *State of the Art and Current Activities*: Lunar Manufacturing with In Resources has an over 30 year study history. Studies indicate that about 90% manufacturing closure for human and commercial support systems can be obtained from Lunar materials[34]. This work has been mostly paper studies and laboratory proofs of concept; however, the necessary technologies in additive, subtractive, formative manufacturing, integrated systems, and solar cell production have a very high terrestrial state-of-the-art. In addition extensive microgravity materials processing experiments have been done in space on Apollo, Skylab, Shuttle, and Spacelab. These experiments include welding, metals solidification, vapor deposition, glass fiber pulling, semiconductor crystal growth, and Lunar equivalent vacuum molecular beam epitaxy crystal growth in the Wake Shield orbital facility. Mars Manufacturing with In Situ

Resources past research also consist of paper and laboratory proof-of-concept experiments, but Mars surface science indicates that near 100% of the manufacturing materials closure can be obtained from Mars surface materials. Studies also indicate that Phobos may facilitate manufacturing in Mars orbit.

- Challenges, Gaps and Risks: The programmatic challenges include adapting processes to take the maximal advantage of and operate properly in the in situ environment (Moon, asteroids, Mars surface etc.). Next, to enable near term programmatic leverage, the first generation facilities need to be engineered to have high product mass to facility mass ratio. Although the in situ manufacturing systems can be human in-the-loop, the expense of first generation life support on the (Moon and beyond) will mandate development of autonomous or tele-operated systems possibly to a greater extent that for terrestrial systems. Our experience working on the Moon suggests that better designs are required for mechanisms to be resistant to the abrasive dusts. Until in situ derived power can provide an energy rich environment, systems will require high energy efficiencies. Processes such as photo voltaic production with Lunar simulant materials have been demonstrated in the laboratory; however the environment and challenges of doing complex manufacturing off Earth are such that early flight demonstration is critical. Systems must be designed "up front" that are repairable by in situ processes. Early investment in repairable design and in flight demonstrations can enable very high leverage to be gained in for over all program cost and otherwise unachievable safety and reliability for all future human space exploration.

Surface Construction

- *Element Description*: Surface Construction for ISRU deals with planetary construction technologies and techniques that use in-situ resources. There are six areas that have been identified as sub capabilities to surface construction these are: site planning, surface and subsurface preparation, structure and habitat fabrication, radiation & micrometeoroid debris shielding, structure & site maintenance, and landing & launch site construction. Each sub capability adds unique technologies and features to the surface construction element.

The thought of construction on another planetary body is often considered a long term goal; however, there is a significant need for the development of some of these technologies early on in the ESMD exploration vision. The ability to have multiple assets on the surface of the moon or Mars that must interact with one another begs the need for a site planning capability. The construction of berms for radiation protection from potential nuclear reactor power supplies is an early need that must also be addressed. As a result even though the construction of landing pads and habitats from in situ materials may be more far reaching, there are other surface construction capabilities that can provide near term benefits.

- *Element Benefits*: Aside from the regularly stated mass savings and cost benefits of using ISRU the surface construction element provides specific benefits which are unique to this area. Site planning provides site surveys and characterization of planetary regolith for construction needs. This capability also assists in the organization of emplaced and future surface assets through civil engineering design, master planning, and architectural layouts. Once site planning has begun it is possible to then provide surface capabilities such as surface and subsurface site preparation. The benefits of this surface construction capability are extensive for long duration missions. The construction of surface transportation infrastructures such as roads, landing and launch pads, as well as providing a utility infrastructure for the site are just a few of the benefits that this capability provides. Site preparation additionally provides dust control and regolith stabilization for surface assets.

Using bulk regolith for a shielding media on the surface of the moon has multiple benefits. These include radiation protection, micrometeoroid and debris shielding, and thermal insulation. This protection is not only needed against natural environments but also human induced conditions such as engine exhaust plume debris and radiation from nuclear reactors. With any long term infrastructure using reusable assets there will be a certain amount of maintenance required. The intent of the structure and site maintenance capability is to provide this maintenance capability to the emplaced surface assets, such as structures, foundations, roads, etc.

The need and benefit of landing and launch pads comes when repetitive landings are required to the same site. A stable landing/launch pad provides a reduction of site degradation by flame and debris ejecta. This also allows for the landing/launch site to be in closer proximity to current and future surface assets. This permanent site provides a centralized location for propellant storage and refueling operations.

- *State of the Art*: With respect to site planning there are commercial off the shelf (COTS) software packages that are available that would require minor updates, and the inclusion of Lunar, or Martian data sets such as terrain maps but would not require significant development work. Architecture and civil engineering disciplines are mature for terrestrial application. Radar/Lidar automated mapping is available and proven on Shuttle missions, as well as robotic orbiter mission to Mars and Venus. Lunar and Martian topographical data sets are partially available, and some geophysical characterization is available for both the moon and Mars.

Surface and subsurface preparation technologies and techniques are very mature for terrestrial applications. While these same machines would not be feasible on either the moon or Mars there is a tremendous heritage that can be incorporated into the design of Lunar and Martian construction equipment. With respect to these machines it should be noted that the state of the art technologies for construction machines may not be the ideal solution to meet ESMD construction needs. Until humans develop a better understanding of working in the new and extreme environments on these planetary surfaces it may suit the exploration community far better to provide simple machines to solve these problems. For example mechanisms such as pulleys, and cables, ramps and levers have a tremendous heritage terrestrially and would not require a great deal of redesign to make them available for early exploration missions. With the correct implementation these simple machines could provide many benefits to early construction over more complex electromechanical devices. With the coupling of suited astronauts and construction equipment an entirely different realm of tools becomes available, such as hand tools including shovels, picks, etc which have been used on the Apollo missions.

Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, including COTS software. These methods consist of things like water-based and waterless concretes, sandbags, blockmakers (compacted soil, carved rock, cast basalt), inflatables, glass fiber and/or rods for concrete reinforcement or as structural elements.

Based on NASA’s current limit of radiation exposure (25 rem/month) less than 5m of regolith (1-2m) can be used to provide acceptable protection from GeV particles, while other radiation risks are mitigated by centimeters of regolith. [Silberberg 1985]. It has been determined that 45.9 cm of regolith (~34cm AL) protects against meteoroid impacts of 7 cm in diameter (1.76×10^{-10} impacts/m^2/yr). Thermal, tests have shown under a few centimeters of Lunar regolith ($2\text{-}4 \times 10^{-6}$ W/cm^2) or in a lava tube produces a nearly constant thermal environment (-35ºC and -20ºC). Micrometeoroid and Orbital Debris (MMOD) concepts and hardware design for ISS currently exist (Aluminum/ Kevlar/ Nextel). In the terrestrial commercial market lead free protective garments are available such as vests, suits, gloves, etc.

In space maintenance and repair are evolving disciplines. New advances in self-healing materials to reduce maintenance, improve reliability and reduce risk are currently being tested within various organizations. The self-healing capabilities of certain polymers have been demonstrated at the laboratory level. At the same time extra vehicular activity (EVA) and intravehicular activity (IVA) repairs are regularly performed on the International Space Station and tile repair tools and materials are being developed as part of return to flight activities for the Space Shuttle.

Apollo style landings on the Moon showed ejecta occurred but did not threaten the landed vehicle. However observations during the Apollo 12 mission that landed near the Surveyor 3 robotic lander showed debris impingement on the Surveyor structure. Mars Viking, Pathfinder, and MER missions have also provided heritage data for Martian landings however these are for much smaller landed masses (~1 metric ton). There is extensive experience with terrestrial launch sites and Earth based propellant and consumables farms.

- *Element Challenges, Gaps, and Risks*: While there are many benefits to developing a surface construction capability for both near term and long term human exploration, and though some of these technologies and techniques are quite mature on Earth, there are many gaps, challenges and even risks that must be addressed, reduced or eliminated. To start there is insufficient scale and resolution of topography for the Moon and Mars in order to provide detailed site planning. In addition architecture and civil engineering disciplines are very immature for non-terrestrial surface applications. The understanding of regolith properties both mechanical and physical at the probable landing/base sites is necessary in order to provide adequate civil engineering design concepts. This data is currently lacking or insufficient.

Another challenge is the design and testing of construction equipment for and in Lunar and Martian environments, plus the development of tele-operated or autonomous surface construction equipment. The advancement of self-healing materials which will also need to be tested in appropriate Lunar/Martian environments is a gap that must be filled, while developing repair techniques that will support planetary surface assets presents yet another challenge.

There also is a significant challenge in using lunar regolith as a shielding material because the regolith material is not ready to be installed immediately. Regolith must be excavated, lifted, dumped, and controlled which requires time, positioning and additional tools and machinery be designed, tested, and deployed. This means that the habitat/crew is not fully protected right away, which may be a risk that mission planners are unwilling to accept. This bulk regolith shielding concept has limitations in that it can only be used to mitigate the effects of thermal, radiation, and meteoroid mechanisms. Other methodologies are needed to combat the atmospheric (Mars), magnetic field, and gravitational field mechanisms that are present.

The development of permanent landing and launch sites are heavily dependant on surface preparation technologies and techniques that are available. The mass, power, volume and reliability requirements are much more challenging for Lunar and Martian propellant and consumables farms. There is also very little known about Mars lightning /electrostatics and Mars weather details. Ultimately the greatest challenge/gap associated with an extraterrestrial landing/launch site is that it has never been done before.

Surface ISRU Product and Consumable Storage and Distribution

- *Element Description:* The Surface ISRU Product and Consumable Storage and Distribution element consists of integrated subsystems required to liquefy, store, transfer and recycle ISRU products. These products are created by the Resource Processing element. The Storage and Distribution system provides these stored commodities to multiple end users and acts as an intermediary for recyclable consumables returned by an end user and sent back to the Resource Processing element.

This element is responsible for liquefying, storing and distributing the mission consumables by utilizing the most power, volume and mass efficient methods available and with as little human intervention and oversight as possible. In general the Resource Processing element provides purified gas streams from the processing reactors to the Consumable Storage and Distribution element where they are stored until needed to support the mission. Liquefaction can be accomplished by passive or active cooling techniques depending on the commodity and surrounding environment. When needed, the commodities are transferred to the end user through pipes or tanker trucks. Transfer of commodities requires umbilical and control systems that carry out operations in an autonomous manner. End users include (as examples); Scientific rovers, pressurized rovers, utility rovers, hopper spacecraft, EVA suits, ascent vehicles, habitats, greenhouses, etc. Those end users that create water or need to recycle it can use the Storage and Distribution center as the drop off point before it is sent back to the Resource Processing element for electrolysis and reuse.

In order to maintain a full cache of propellants and consumables, leak detection and mass verification sensors are used to verify commodities are available at mission critical quality and quantity. Health management, autonomous monitoring and control, and hazard mitigation and recovery capability are required to support this element.

- *Benefits of Storage and Distribution Systems:* The Storage and Distribution element benefits all ISRU supported architectures by enabling long term, zero-loss storage of ISRU propellants and consumable products. This allows longer ISRU production times (enabling smaller, less power hungry processing systems) and ensures verifiable mission critical products (return propellants and emergency life support consumable caches) are available prior to committing the crew for launch from earth or descent to the surface from moon/mars orbit.

Once all mission consumables are stored, the Storage and Distribution element preserves these caches in a zero loss state until needed. At a fraction of the power consumed during the initial production and liquefaction phase, the system can maintain these caches of consumables indefinitely.

- *State of the Art and Current Activities*: Autonomous control of dynamic processes involved in transfer of cryogenic fluids is currently at a TRL2/3 with a degree of difficulty of II/III. Deployable storage for cryogenic systems is at a TRL of 2 with a research degree of difficulty of III. Autonomous umbilicals have a TRL of 4/5 with a research degree of difficulty of I. Integrated liquefaction systems of the capacity needed for human missions is a TRL of 2 with a degree of difficulty of II for LO_2 systems and TRL of 1 and degree of difficulty of III for Hydrogen systems.

Exploration funded activity in support of this element include ‘Integrated ISRU for Human Exploration’ which features a pulse tube cryocooler for LO_2 liquefaction and a lightweight, rigid storage tank and ‘High Energy Density Power System’ that features a lightweight, high pressure gas storage system for fuel cell reactants. Both of these development contracts are being performed by Lockheed Martin.

In the past, the Small Business, Innovative Research program has funded several technology development efforts dealing with insulation systems, cryocoolers, automated umbilicals, etc. that can be used as a starting point for some aspects of the Storage and Distribution element.

- *Challenges, Gaps and Risks*: The main challenges associated with Storage and Distribution are those associated with creating a highly reliable system that can operate in a harsh environment for hundreds of days with minimal human oversight, only robotic tending maintenance and capable of being launched from earth with minimal launch mass and volume.

- **Deployable Systems**: Without ISRU, return propellants and life support consumables must be transported from earth, requiring a significant portion of both mission launch mass and volume be dedicated to these commodities. The ISRU Resource Processing element subtracts the propellant and life support consumable mass from this inefficient and costly architecture but it is up to the Storage and Distribution element to provide as much volume savings as possible. Flying empty, fixed volume tanks to store the ISRU products does nothing to reduce the launch volume required from earth. Therefore a significant challenge to the Storage and Distribution element is to develop storage systems that store as compactly as possible for launch and can be easily deployed on the Lunar or Mars surface without hands on human presence. There is currently no funded activity in this technical area.
- **Highly reliable, large Scale Cryocoolers/Refrigeration**: Today's space certified cryocoolers are in the 10 Watt/ 80K class – capable of cooling sensors to liquid oxygen temperatures. For ISRU propellant liquefaction, highly reliable refrigeration systems must be developed that provide hundreds of watts of cooling down to liquid hydrogen Temperatures (20K). These systems must be able to operate for hundreds of days without maintenance. There is currently one funded project advancing the state of the art in Liquid Oxygen Cryocoolers, there is currently no significant work on a large Hydrogen cryocooler (the more difficult of the two).
- **Long Life Sensors/Instrumentation:** highly reliable instrumentation that does not require traditional calibration are needed to support ISRU systems. There will not be a human presence at these sites to perform calibration functions, yet ground controllers must have confidence in the instrument readings to assure the proper quantity and quality of propellants and consumables are present before authorizing the crew launch. There is a small amount of development work going on in this area.
- **Autonomous Control of Dynamic Processes:** Autonomous control of spacecraft has been validated on spacecraft like Deep Space 1. However, these control functions used discrete on/off indicators to perform spacecraft control. The liquefaction and distribution of cryogenic fluids is far from an integrated set of discrete sensors. New algorithms and control architectures must be developed and tested to validate an autonomous control system is capable of performing this function. Communication time delays prohibit the real time, human control authority we rely on to safely load the launch vehicles at earth based spaceports. There have been several proposals in this development area but as yet no multiyear funding to develop these needed control systems.
- **Integrated Earth-based proving ground:** The integration and maturation of these technologies to perform the Storage and Distribution function will require years of development and testing before we are ready to demonstrate human scale systems that are mass and volume efficient and reliable enough to demonstrate fully autonomous operation for hundreds of days on the moon or Mars.

The Storage and Distribution element of ISRU has the potential to enable significant mass and volume savings, creating a cascade of lower life cycle costs across the entire Exploration program. Our greatest risk is putting off the necessary planning and development stages for these systems until it is too late to effectively influence the architecture design. Without the maturation of technologies and trust of the architecture designers in the benefits of a robust ISRU supported architecture, we will end up with heavy, bulky, unreliable systems that require many more launches per mission and a ground control army to monitor every piece of equipment.

ISRU Unique Test & Certification

- *Element Description*: The ISRU Unique Test and Certification element includes the set of capabilities needed to support the development, test, and certification of all of the ISRU technologies and capabilities. It includes three main focus areas: modeling and standards, simulants, and unique test environments.

Modeling includes the capability to model ISRU components and systems to analyze and predict engineering performance and system requirements. An example of engineering performance would be the percent of oxygen that a given process removes from a given lunar raw material. System requirements are inputs to the system such as power, reagents, and mass of components. Modeling also includes the capability to characterize and model the behavior of extraterrestrial soils and granular flow. The standards subelement includes standardized procedures and guidelines for the use of soil simulants, for environmental testing, for life/cycle tests, and also a standardized set of metrics for the modeling and technology comparisons.

The simulants sub-element focuses on the capability to create simulated lunar and Martian regolith, rock, and dust from terrestrial geological materials such as rocks, basalts, and other minerals. Simulants also includes the careful mixture of gases and dust to simulate the Martian atmosphere.

The unique test environments sub-element includes the capability to recreate in a terrestrial test site the extreme environments of the moon and Mars. This includes environmental simulation such as thermal extremes, low vacuum, thermal cycles, simulated atmosphere (including dust and wind), radiation, and surface and sub-surface conditions. This sub-element also includes the simulation of micro-gravity, lunar and Mars gravity, and low-gravity found on planetary moons or other bodies.

The Unique Test and Certification element relies on the other ISRU elements to provide the unique or hardware-specific requirements definitions, and also to specify the timeframe that the test or modeling capability is required.

- *Benefits*: The primary benefit of a modeling capability is that it enables apples-to-apples comparisons of ISRU technologies. For example, there are many possible processes for extracting oxygen from the lunar regolith, and a consistent modeling capability will allow all alternatives to be evaluated based on common inputs, assumptions, and clearly defined figures-of-merit. In addition, concurrent development and validation of ISRU soil, component, and system models with ISRU technology will reduce design, development, test and evaluation (DDT&E) time and costs by helping to direct resources to the technologies that offer the highest benefits if completed or improved. In addition, the unique environment at the moon and Mars may limit the ability to conduct complete final flight validation by testing alone, and well-developed and validated models may fill the gap.

The capability to produce large quantities of accurate simulants will ensure that tests conducted on physical (e.g. excavation, transport) and chemical processes are relevant and properly address key driving forces and processes. A simulant capability will also avoid depleting existing collections of lunar and meteorite samples, will provide large quantities of materials to test and validate designs, and will provide a substitute for Martian soil in the absence of Mars samples. Proper simulants, especially dust simulants that are less than 20 microns in size, will also benefit validation tests for other flight hardware such as landers, habitats, and EVA equipment.

The capability to carefully simulate the actual operating environment in a terrestrial test facility will provide a significant reduction in risk and cost of developing and implementing ISRU technologies and capabilities. For example, before the Apollo missions, the lunar dust environment was not properly simulated (due to lack of specific data on lunar dust). The result was severe space suit degradation during the mission and detrimental effects on the astronaut health from dust migration into the habitat module. Ground tests performed in the proper environment can identify potentially fatal design flaws while there is still time for changes. Ground testing also allows post-test access to the hardware for analysis and modifications.

- *SOA and Current Activities*: There is extensive literature on terrestrial soil mechanics that may not translate well to the lunar regolith because of differences in size, moisture content, gravity, and magnetic properties. The terrestrial powder industry uses an elaborate bench-top-to-full-process-plant development process that can be extremely expensive and time-consuming. Granular flow clogging is a common industrial problem with 'kick-the-chute' solutions that are not feasible for a processing plant based on the moon.

ISRU component models of varying fidelity have been developed in individual projects to support very specific short-term studies and goals, and these have been primarily focused on the chemical processing and storage capabilities. An ISRU economic system model is in development by the Colorado School of Mines, but this requires technical inputs from the component models that are not yet developed.

Lunar simulants have been produced in the past. For example, approximately 27,000 lbm of JSC-1 lunar simulant was produced in 1993. It represented an average chemical composition between the highlands and mare regions of the moon, and is no longer available. The MLS1 lunar simulant produced in 1987 is also no longer available. FJS1 lunar simulant produced in Japan is currently available in modest quantities. Martian simulants produced to date have focused on specific features of the regolith, such as the JSC Mars-1 simulant chosen for a reflectance spectrum close to the Mars bright areas.

Test chambers exist that can simulate and control to the full thermal range of the lunar and Mars environments. The best vacuum that medium and large chambers can achieve is between 10^{-6} and 10^{-8} torr, which is below the 10^{-10} and 10^{-11} torr of the lunar day/night and poles. These chambers offer a mix of required capabilities in terms of size, and ability to handle simulants, to control to more than a single set temperature, and to provide remote manipulation to set up simulants in the vacuum environment. For the Martian dust storms, there is a Mars Wind Tunnel at NASA Ames that can simulate the winds and dust up to 100 m/s, but it lacks a thermal simulation capability. Other chambers have operated with simulated Mars dust and atmospheric gas mix, but without wind simulation.

Current state-of-the art for gravity simulation for short durations includes drop towers (5.2 sec max, micro-g only), reduced-gravity aircraft (20 sec micro-g, 30 sec lunar-g, 40 sec Martian-g), and sounding rockets (5 to 6 minutes). For long duration micro-gravity testing, there is a glove-box on the ISS, and two new integrated experiment racks scheduled to be delivered to the station in May, 2007 (Combustion Integrated Rack, Fluids Integrated Rack). There is no capability for long-duration testing at lunar and Martian gravity without going to the site.

- *Challenges*: Although lunar regolith is fairly homogenous compare to Earth, the various minerals are found in different concentrations in different locations. For example, the anorthositic mineral, which contains most of the lunar aluminum, is found mostly in the lunar highlands, while the ilmenite minerals, which have a high concentration of iron, are predominantly in the lowlands, or mare, regions. The development and selection of chemical processing capabilities will depend on the intended lunar feedstock. Different lunar simulants will be needed to test the different processes. Although less data exists for Mars, it is thought that the Martian regolith is even more diverse, especially when it comes to water content in the soil. The tendency will be to create a unique simulant for every area, which could become costly and defeat the benefit of comparisons between different development projects. The challenge will be to develop root simulants for a few components (e.g. basalt-rich lowlands, anorthite and feldspathic basalt highlands, pyroclastic glass), and then develop derivative simulants from a mixture of the roots to reflect the mineralogical diversity of specific locations and to maintain scientific control of tests.

Vacuum test chambers that introduce dust and regolith simulants may never be able to regain a high cleanliness rating required for other capability development such as advanced telescopes and observatories. The challenge will be to convince certain facilities to become "dirty" facilities with sufficient long-term test possibilities that these "dirty" facilities will not be hurt by the potential loss of test programs that require "clean" facilities.

Because of the lack of long-duration reduced gravity simulation capability, there will be a challenge to determine which technologies and processes from the ISRU capabilities are gravity-dependent. This includes determining whether micro-gravity tests will be sufficient or appropriate, or whether actual gravity-level simulation is required.

- *Gaps & Risks*: Significant gaps exist in the development of granular flow models and regolith characterization. These range from a lack of detailed knowledge of the Martian regolith composition, fabric, and microstructure, to the role of tribo-charging, electrostatics, ice composition, and reduced gravity in soil behavior. ISRU technology component models are required that allow parametric inputs for sub-component performance in order to identify the effect on the total component performance. End-to-end system models are required that will aid in creating the most beneficial total system.

Accurate dust simulants below 20 microns are needed immediately for the proper development of ISRU processes and capabilities as well as every other technology and capability that will need to operate on the lunar surface. In addition, simulant materials are needed that represent the various regions of the lunar surface, such as anorthite minerals to represent the highland (including the polar regions), and agglutinate (glass) fractions, which represent up to 40 percent of the typical lunar regolith mass.

Vacuum chambers that are tolerant (and willing) of using simulants on a large scale are required, as well as remote equipment to handle, distribute, and charge simulants within the evacuated vacuum chamber. There is no capability for long-term simulation of reduced gravity, and it is unlikely that one will be built unless a free-flying centrifuge or tethered facility is funded. Currently we must send robotic demos to prove out reduced gravity capability, and the opportunities for these flights are limited. There is also no medium-to-large scale integrated test capability that can duplicate the thermal, vacuum, dust, *and* gravity environment simultaneously.

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Acronym and Abbreviation List

AEDC	Arnold Engineering and Development Center
Al	Aluminum
atm	Atmosphere
Ar	Argon
ASARA	As Safe As Reasonably Achievable
CO_2	Carbon dioxide
COTS	Commercial Off The Shelf
CRL	Capability Readiness Level
CSM	Command and Service Module
DDT&E	Design, Development, Test, & Evaluation
DoD	Department of Defense
DRM	Design Reference Mission
ESMD	Exploration System Mission Directorate
EVA	Extra-Vehicular Activity
Fe	Iron
FDIR	Failure Detection, Isolation, and Recovery
g	Gravity
GEO	Geo-stationary Earth Orbit
GRC	Glenn Research Center
^3He	Helium-3 isotope
H_2	Hydrogen
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
IVA	Intra-Vehicular Activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
kg	Kilogram
KSC	Kennedy Space Center
L1	Lagrange Point L1
LEM	Lunar Excursion Module
LEO	Low Earth Orbit
LO_2	Liquid oxygen
LRO	Lunar Reconnaissance Orbiter
MER	Mars Exploration Rovers
MMOD	Micro-Meteoroid Debris
MSFC	Marshall Space Flight Center
MT	Metric Ton
MW	Mega-watt
NASA	National Aeronautics and Space Administration
NTR	Nuclear Thermal Rocket
O_2	Oxygen
ORU	Orbital Replacement Unit
RD^3	Research and Development Degree of Difficulty
RWGS	Reverse Water Gas Shift
Si	Silicon

SOA	State-of-art
SOE	Solid Oxide Electrolysis
Ti	Titanium
TRL	Technology Readiness Level