# NASA
# In-Situ Resource Utilization (ISRU) Capability Roadmap
# Executive Summary

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## 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.)[h], vast quantities of metals and minerals, atmospheric constituents, unlimited solar energy, regions of permanent light and darkness, and the vacuum and zero-gravity of space itself. 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 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 and possibly 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 making propellants in-situ can significantly reduce mission mass and cost, and also enable new mission concepts, such as 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 will 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 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 on Missions & Architectures

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

| 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 |
| | Shielding for habitat shielding (radiation, micrometeroid, & exhaust plume debris) and surface nuclear power (radiation) 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 mass leads to reduction in launch costs |
| | Reuse of elements leads to reduction in mission costs |
| | Use of modular, common hardware with propulsion, life support, & mobile fuel cell power systems leads to reduction in DDT&E costs |
| | ISRU enabled missions lead to reduction in architecture costs through elimination of separate dedicated missions |
| | 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 & repair |
| | Reduction in mission risk due to dissimilar redundancy of mission critical system |
| | Reduction in mission & 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 hoppers |
| | Increased delivered and return payload mass through ISRU |
| | Reduced cost missions to Moon & 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 & 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 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 Mars ascent vehicles. 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[a,b] that for every kg delivered to the Mars surface 3.5 to >5 kg are required to be delivered to low Earth Orbit. 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 ISRU plant. 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 shielding (radiation, micrometeoroid, & 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 criteria 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 greatly change what 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[d]. 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 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.

- *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 above 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 electrical generation systems in 1MW class compared to Earth delivered hardware[i].

Cost Reduction Benefits

- *Reduction of 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 less 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 leads to reduction in mission costs.* Recurring costs for transportation elements, such as transfer stages and landers are expected to by in the $10's M if not low $100's M. **** Find Apollo LEM and Service Module costs***. Designing systems for reasonable reuse before discarding (5 to 10 times) could provide significant immediate and long-term savings compared to the extra Design, Development, Test & Evaluation (DDT&E) and certification costs required for developing moderately reusable systems.

- *Use of modular, common hardware with propulsion, life support, & mobile fuel cell power systems leads to reduction in DDT&E costs.* A significant number of the technologies, components, and subsystems associated with in-situ resource utilization are common with life support, fuel cell power, and propulsion systems. Examples include valves, water electrolyzers, phase separators, heat exchangers, gas & cryogenic storage, etc. With pre-planning a large number of these components and subsystems can be used in multiple systems. Understanding of processing/usage rate requirements can further lead to development of modular, interchangeable components and replacement units, that if sized properly can also support logical redundancy levels or degraded modes of operation with failure. 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.

- *ISRU enabled missions lead to reduction in architecture costs through elimination of separate dedicated missions.* In-situ propellant production, combined with reusable systems such as hoppers, can be used extend surface exploration without the need for separate dedicated missions. In a recent study[c], 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.

- *Cost reduction through commercial sector participation*. ******More work********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 propellant plants could be designed and built by private enterprise; propellant could be purchased by NASA (or other commercial entities) at the Moon for use as needed. Lunar industrial plants may produce electrical power through solar energy conversion for both in-situ infrastructure growth as well as eventual use on Earth. Helium-3 production could allow large-scale fusion reactors to become feasible on Earth. Near-Earth and main belt asteroids between Mars and Jupiter are rich in cobalt, nickel, platinum, and other precious metals that, if mined, could be worth billions of dollars.

## 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 multiplication of the risk 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 & 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 mission success.

- *Reduction in mission risk due to dissimilar redundancy of mission critical systems.* Redundancy is the preferred method of ensuring system reliability 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, & 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 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 greatly change what 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, the greater the distance required, the greater risk to deployment success. Surface mobility units for ISRU could possibly be used for reactor deployment, besides berm shielding replacement.

- *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 umbilical to replenish EVA suits while traversing to the next site of exploration. Should a component on the EVA suit fail, scavenging 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 extend surface exploration without the need for separate dedicated missions.

- *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 later carry an increased payload mass to the surface equal to the ascent propellant load if in-situ propellant production is incorporated.

- *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 would significantly reduce the Earth launch vehicle lift-off weight (~2/5) compared to the non-depot option due to the significant reduction in mission Delta-V ($\Delta V$) for propellant delivered from Earth to $L_1$ compared to the $\Delta V$ from the lunar surface to $L_1$ (~1/5)[f]. Not only do the Earth launched transportation vehicles avoid carrying the return propellant, but also the propellant required to transport the return propellant. Not only do the Earth launched transportation vehicles avoid carrying the return propellant, but also the 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[g].

- *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. To provide this confidence, while providing immediate payback to the mission, ISRU can be incorporated 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, 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 extend? | 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 & life support? | 2010 to 2012 | Determines long term sites for Lunar bases and transportation architecture |
| Is water readily available on Mars for propellants & 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 extend*? 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' then 'if'. Since no 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 the technologies (and often the actual hardware) for propellant production from the Mars atmosphere are the same as those used 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. Besides making this propellant combination even more beneficial, if water is readily available on Mars oxygen and hydrogen propellants can 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 may make the use of hydrogen fuel unattractive. In-situ production of methanol, ethylene, aromatics (benzene & 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. Carbon monoxide is also a potential

Mars produced fuel, however its low performance and low density cryogenic fluid characteristics make it only attractive for 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. This may lead to non-optimal Lunar mission lander and transfer stage designs. Early demonstration of methane production from lunar soils (solar wind implanted carbon and hydrogen) 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 provides 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 extend 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 then for a NASA-only program. For NASA to obtain the greatest benefits of space commercialization, the US government & NASA must initiate multiple activities as soon as possible, such as anchor tenancy and service , favorable space legislation and regulations (tax incentives, property rights, liability, ITAR / export control), challenges, etc.

- *Is long-term human presence on the Moon a goal?* The primary purpose of human lunar exploration is as a testbed for human Mars exploration. However, if long-term presence on the Moon is 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 the architecture. 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 achieve these benefits in a timely manner.

- *Is water readily available on the Moon for propellants & 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 L1, Earth orbit, etc. and electrolyzed at the site of final destination.

- *Is water readily available on Mars for propellants & 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 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 soils 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 may 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 then access to surface (<1 meter) water in regolith due to the higher complexity, reduced surface exploration location possibilities, and possibility of actual life associated with underground liquid water. 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 & 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 whether telescopes need to be assembled in space |
| Surface Power-Solar vs Nuclear | 2009-2010 for Lunar base, 2015-2020 for Mars base | Determines size and operation duration 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 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 placement of ISRU, 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 may 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 redundancy). The growth in ISRU can lead to use of surface hoppers to meet the original goals of multiple individual missions.

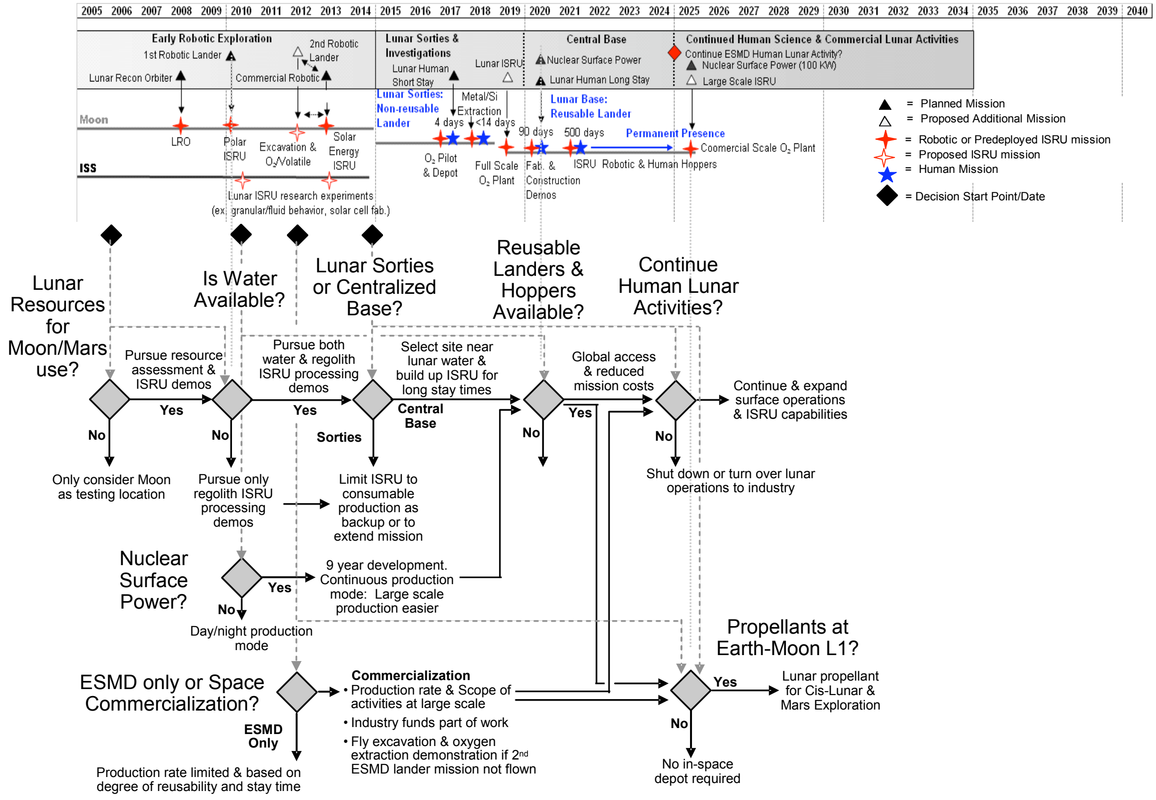
- *Pre-Deploy vs All-in-one Mission:* Some mission studies have recommended missions that delivery everything needed to the surface in one vehicle to eliminate the need for precision landing as well as concerns with landing aborts if pre-deployed assets are critical for crew and mission success. The 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 dependant on the real-time successful operation of ISRU and power systems. Since all missions are dependant on multiple systems working successfully, this may or may-not be a selection discriminator.

- *Direct Return, Low Orbit Rendezvous, or L1/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 are selected to minimize lander/ascent vehicle size. This requires an increase in both capture orbit propulsion needs and return to Earth propulsion needs. 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 equates to X kg in LEO. 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. 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 a dedicated Earth return stage element..

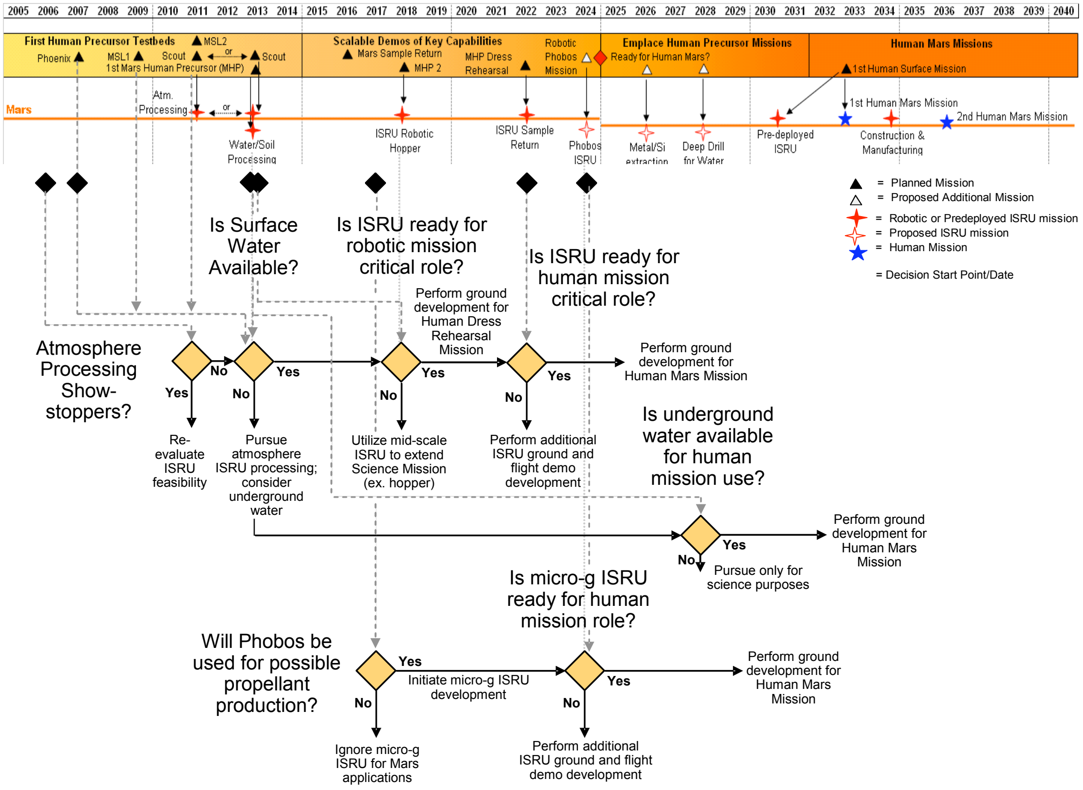
- *Surface Power-Solar vs Nuclear.* As mentioned previously the size of ISRU plants is based on the total production need and duration of operation. Because many ISRU processes are power intensive, if solar power is utilized, operations may only be possible during sunlit durations. This means ~12 days 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. Therefore, for the same total production need, an ISRU plant using nuclear power may operate at half the production rate for a Lunar solar-powered ISRU system and at a third of the production rate for a Mars solar-powered ISRU system. However, the ability to in-situ manufacture power generation and storage systems and the use of near-permanent sunlit locations on the Moon could delay or eliminate the need for nuclear surface power on the Moon, besides as a testbed for Mars.

- *Abort-to-Surface or Abort-to-Orbit.* The Apollo Lunar Excursion Module (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 Command and Service Module were above in low Lunar orbit. The use of in-situ produced propellants for ascent propulsion needs precludes the use of abort-to-orbit failure recovery. Instead, an abort-to-surface scenario is required to be compatible with ISRU. As long as landing system redundancy can provide a close landing to the ISRU plant and surface habitat, ISRU-based life support, manufacturing, and construction capabilities can significantly increase long-term crew survivability.

## Lunar ISRU Missions & Decision Points



## Mars ISRU Missions & Decision Points



## ISRU Emphasized Architectures for Moon & 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) verses 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[e]. For Mars, sample return missions with in-situ propellant production as well as the human Mars Reference Mission[a] 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[f,g]. The resent 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 with 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. For this final report, top-level mission objectives and dates were provided. Additional missions are recommended 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 (Option C Early Lunar Resources) as well as the Mars Strategic Roadmap team.

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

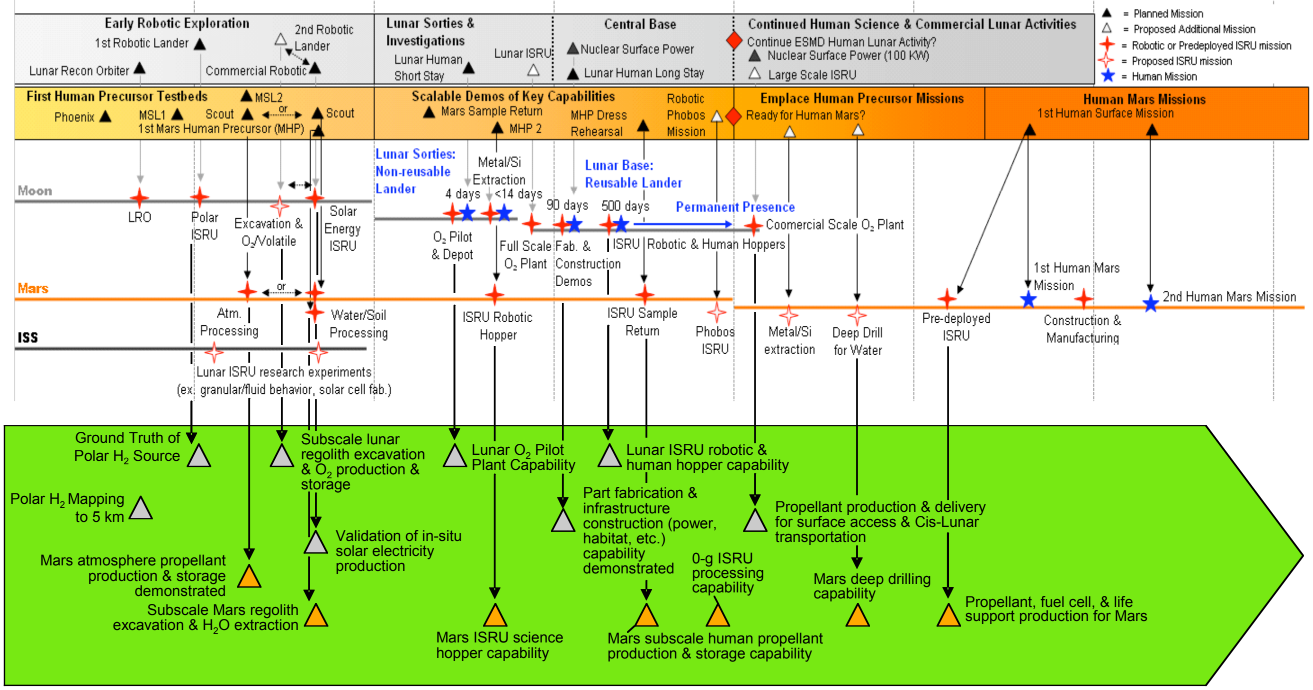
- No Earth launch vehicle assumption was made; Benefits were based on projected reduction in payload needs to LEO
- Crew of 4 or 6 assumed up to permanent presence; TBD (12) at permanent presence
- Need to characterize resource, environment, & engineering unknowns as early as possible
- Utilize ISS for 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 & Investigation phase to support use of ISRU and reusable systems at 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 compared to missions which 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 are confident 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 & quantity of products. Capabilities need to grow on an as-needed basis 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 capability.

## 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, early Lunar robotic and human missions will demonstrate ISRU concepts, technologies, & hardware that 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) Cryogenic fluid storage & transfer. Since these concepts, technologies, and hardware are applicable to both the Moon and Mars, early demonstration also supports sustained human presence on the Moon. Another 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, (d) ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals. The making and transferring of mission consumables and landing near pre-positioned ISRU with empty tanks are critical to achieve 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 and 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 is critical as early as possible, 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 which enable new exploration options, such as reduced size lander/ascent vehicles, surface mobility & hoppers, power-rich distributed systems, enhanced radiation shielding, manufacturing/construction, etc. should be pursued in an evolutionary approach. Early demonstrations are required experiment development time, 26 month gaps in missions, trip times, and extended surface operations mean 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 before human mission is recommended.

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.

## Critical/Enabling ISRU Capabilities

*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 experience. Extensive terrestrial experience | 2010 (demo)<br>2017 (pilot) |
| Lunar Oxygen Production From Regolith | Sustained lunar presence and economical cis-lunar transportation | Earth laboratory concept experiements; TRL 2/3 | 2012 (demo)<br>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)<br>2017 (pilot) |
| Mars Water Extraction From Regolith | Propellant and life support consumable production w/o Earth feedstock | Viking experience and Phoenix in 2007 | 2013 (demo)<br>2018 or 2022 (subscale) |
| Mars Atmosphere Collection & Separation | Life support and mission consumable production | Earth laboratory & Mars environment simulation; TRL 4/5 | 2011 (demo)<br>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)<br>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)<br>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)<br>2020 (pilot scale) |
| In-Situ Surface Power Generation & Storage | Lower mission risk, economical outpost growth, and space commercialization | Laboratory production of solar cells at <5% efficiency | 2013 (commercial demo)<br>2020 (pilot scale) |

# 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

Interdependency with Propulsion

Interdependency with Surface Mobility

Interdependency with Human Support Systems

## Technical & Programmatic Challenges

| *Major Technical Challenges (Top 10 Maximum for Table)* |
|---|
| **2006-2010** |
| ▪ Lunar dust mitigation<br>▪ Operation in permanently shadowed lunar crater (40K)<br>▪ Regolith excavation in harsh/abrasive environments |
| **2010 - 2015** |
| ▪ Large scale oxygen extraction from regolith<br>▪ Autonomous operation & failure recovery<br>▪ Day/night operation (startup/shutdowns) without continuous power<br>▪ Efficient water extraction processes<br>▪ Modular, mass-efficient manufacturing and initial construction techniques |
| **2020 and Beyond** |
| ▪ Long duration operations with little/no maintenance (300+ sols on Mars)<br>▪ Habitat and large-scale power system construction techniques |

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

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

Material Handling & Transportation

- Extra-terrestrial experience in handling and transporting native materials is very limited for Moon (Apollo samples were manually manipulated for encapsulation 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 little development money 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 [r,s,t]. 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.

- 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, it's CRL is 3 and an RD$^3$ level of I.

- 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 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 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.

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 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: MMOD concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel)
- 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 vehicle (23 metric Ton landed Mass)

Surface ISRU Product and Consumable Storage and Distribution

- Limited size and capacity cryo-coolers have flown (science instruments)
- Cryogenic fluid storage systems has 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 development of ISRU technologies and systems to date have been for oxygen production from lunar regolith, construction feedstock production (cement and bricks) from lunar regolith, and propellant 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
- Low-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 are very immature
- Development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment is required
- Processes to extract and produce oxygen and manufacturing and construction feedstock from regolith are very immature.
- Tele-operation and/or automation of robotic excavation, transportation, and construction processes are very immature
- Dust insensitive fluid couplings and leak detection in open vacuum or low atmospheric environments
- 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 is very immature

## 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 will 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 of 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

1. What are the critical workforce competencies needed to execute this roadmap?

2. Where do the competencies currently exist (within NASA, NASA contractors, industry, academia, other government)?

3. Are there any special Human Capital planning considerations that the team thinks should be highlighted?

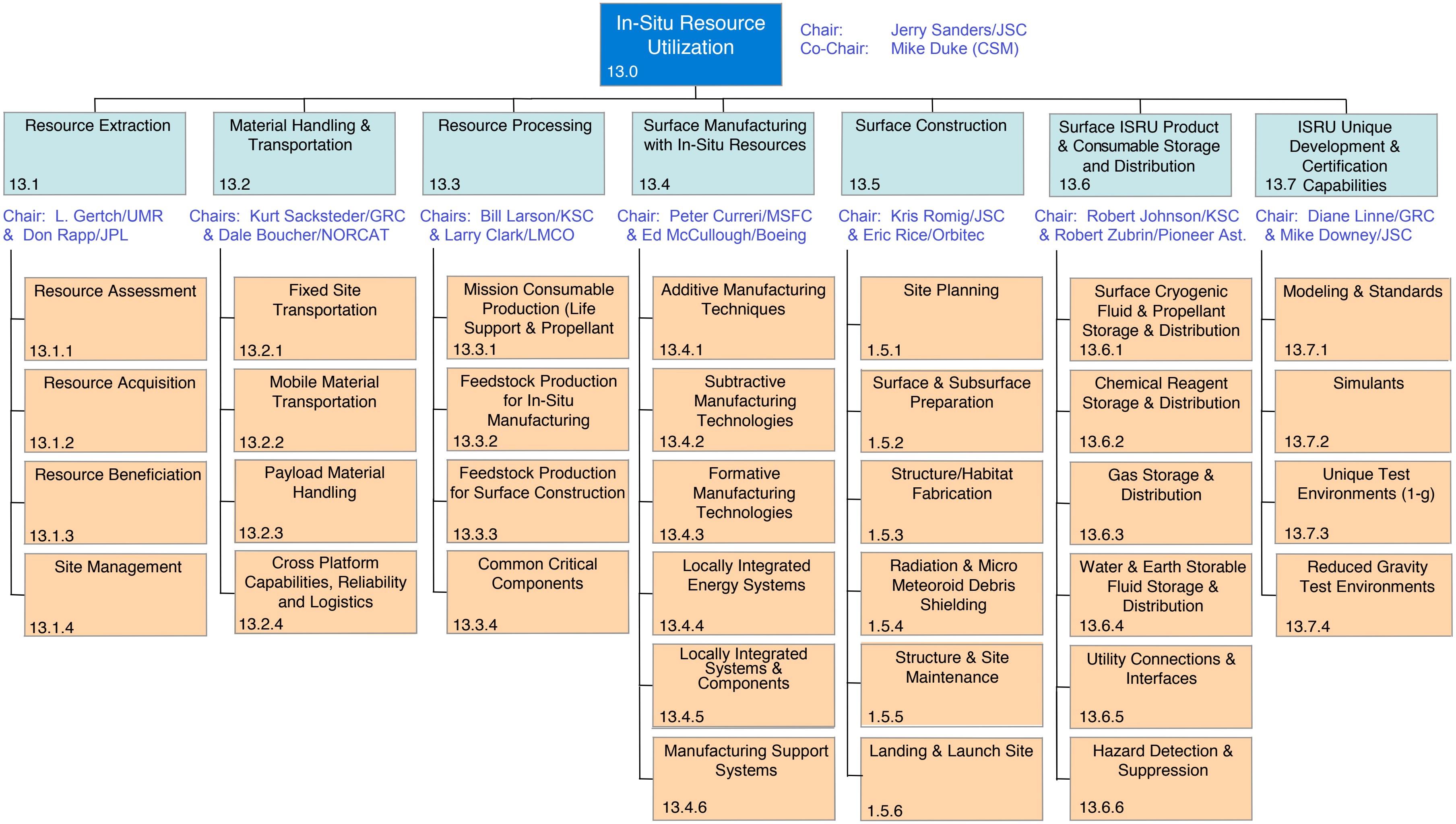
**Facilities (or other physical infrastructure):**

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

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

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

**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 Capabilities 13.7 — 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

## 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

### Material Handling & Transportation

### 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 and oxidizer to return the Astronauts to Mars orbit. That exceeds the capability of any launch vehicle currently in production.[k,l] Even if we still had a Saturn V available, the Mars ascent propellant would consume 43% of it's payload capability. So it becomes very clear that propellant and oxidizer manufacture 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 ration.

| **Mission Name** | **Propellant Produced (mt)** | **ISRU Plant Mass (mt)** | **Mass Seed Hydrogen (mt)** | **Mass To Surface Saved (mt)** | **Mass <u>In</u> LEO Saved (4:1) (mt)** |
|---|---|---|---|---|---|
| Bimodal NTR [m] | 39.5 | 2.4 | 4.1 | 33.0 | 132.1 |
| DRM 3 [n] | 39.0 | 3.9 | 5.4 | 29.7 | 118.8 |
| DRM 3 [o] (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 [p] | 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 for 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 important to have the capability of producing life support 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 insitu repair capability. It would be impossible to carry a spare part for every component 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. Intelsat is a good example of this model.

- *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 CO2 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.[q] 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 reaction and Cold Plasma CO2 Dissociation. The first two listed have had extensive prototyping and testing completed. Solid Oxide Electrolysis 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

- *Element Description:* Surface Manufacturing with In Situ Resources is a set of capabilities which 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[i]. 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[j]. 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

Surface ISRU Product and Consumable Storage and Distribution

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