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LUNAR IN-SITU RESOURCE UTILIZATION IN THE ISECG HUMAN LUNAR EXPLORATION REFERENCE ARCHITECTURE

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In May 2007, the "Global Exploration Strategy (GES): The Framework for Coordination" document was published, signed by 14 international space agencies to present a vision for a coordinated approach to robotic and human space exploration, with a focus on destinations within the Solar System where humans may one day live and work. Later the same year, and based on this document, these fourteen space agencies established the International Space Exploration Coordination Group (ISECG) – a voluntary, non-binding international *coordination mechanism* with the intention of providing a framework to coordinate space exploration efforts across the globe. In July of 2008, the members of the ISECG agreed to collectively explore ideas and plans for human exploration of the Moon as a first step in jointly defining objectives and mission scenarios, with the goal of defining a global reference architecture for human lunar exploration by mid 2010. In support of this effort, a Campaign Integration Team and a number of Function Teams were established by the ISECG under the auspices of an International Architecture Working Group (IAWG), consisting of representatives of interested space agencies, to define the purpose, critical functions and technologies, incorporating strategic guidelines, and hardware elements needed to meet the goals and objectives for human exploration of the Moon established by the ISECG. This paper will present an overview of In-Situ Resource Utilization (ISRU) development activities and areas of interest of the international space agencies participating in the ISECG process. A brief summary of the ISECG Reference Architecture for Human Lunar Exploration will also be given highlighting the common goals and strategic guidance which drove the architecture development. The main focus will be on the approach followed to incorporate ISRU into the lunar exploration campaign, detailing the various key considerations, including the rationale for demonstration, pilot and full implementation system deployment, with the overall objective being to enable long-term sustainability. A description of the ISRU elements under consideration will also be given. Finally, the various options possible for international collaboration will be reviewed, together with past and previous ISRU-related analogue field testing and possible future robotic precursor flight opportunities.

I. INTRODUCTION

The International Space Exploration Coordination Group (ISECG) Reference Lunar Architecture was the first attempt to incorporate In-Situ Resource Utilization (ISRU) into an international human lunar exploration plan. To perform this effort, a Campaign Integration Team and several Function Teams were established to define the purpose, critical functions and technologies, incorporating strategic guidelines, and hardware elements needed to meet the goals and objectives for human exploration of the Moon established by the ISECG. ISRU involves the extraction and processing of local resources, both natural and discarded, into useful products and services, and covers a broad range of surface activities and technical disciplines. The ISRU Function Team was tasked with identifying functions and operations associated with these processes and services that could be developed into discrete elements to support an international collaborative campaign of lunar missions. While some ISRU aspects and capabilities were included in the final Global Point of Departure (GPoD) architecture, because ISRU has never been flown before and knowledge of ISRU capabilities and concepts were new to many of the participants, many ISRU functions and benefits were left out in this first reference human lunar architecture.

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II. OVERVIEW OF ISECG REFERENCE ARCHITECTURE[1]

The ISECG Reference Architecture for Human Lunar Exploration, or Global Point of Departure ("GPoD") as it is commonly known, is a conceptual description of a series of elements delivered to the lunar surface over time, and a concept of operation that enables commonly agreed exploration goals, including science and Mars mission preparatory objectives, to be met. This reference architecture describes both human and automated missions to the Moon, as well as a robotic precursor phase that prepares the way for the ultimate arrival of humans. It furthermore provides a conceptual definition of the different transportation and lunar surface systems performing the various functions required for addressing the common lunar exploration goals. It provides optional scenarios for continuing human exploration in a sustainable manner and building on earlier achievements.

The architecture was developed under the guidance of International Architecture Working Group (IAWG) and International Objectives Working Group (IOWG) by the Campaign Integration Team supported by dedicated Function Teams for each of the following major functional areas: Habitation, Mobility, Transportation, ISRU, Power, Servicing and Communications and Navigation. These Function Teams defined a series of notional elements which enable lunar exploration in a coordinated way that address the common goals. The GPoD architecture was anchored in a set of Ground Rules and Assumptions (GRAs) and derived a series of functional elements and associated concepts of operation within the GPoD campaign to demonstrate a notional closed architecture. The architecture was further developed by conducting trade studies and by analyzing variations and sensitivities around the reference baseline. In addition, game changing technologies and approaches, in some cases outside the original GRAs, were revealed during the process.

Developed by ISECG participating agencies, the lunar GPoD architecture represents an emerging international consensus on a sustainable and robust approach for lunar exploration. It demonstrates the importance of agencies working together early in program formulation. While it is neither a lunar outpost nor a series of Apollo style missions, the GPoD reflects expected global budgetary challenges while enabling significant scientific and exploration objectives to be met and reduces risk for future exploration. The GPoD is a flexible approach to lunar exploration that can accommodate changes in technologies, international priorities and programmatic constraints as necessary. Opportunities for multiple partners and a phased approach that is driven and informed by discoveries and accumulated experience are key to the architecture's robustness.

Notional exploration locations considered for this campaign are based upon evolving remote observations and studies. NASA Lunar Reconnaissance Orbiter (LRO) mapping objectives include 50 high priority regions of interest for human exploration of the Moon, based on results from the Clementine and Lunar Prospector missions and previous site selection studies. These regions of interest are not intended to be, and are not to be interpreted as, a site selection activity for actual landing sites. Rather, they illustrate the diversity of scientific and resource opportunities, and geographic terrains and locations that together form a representative basis for scientific exploration, resource development, and mission operations. A subset of these regions of interest were selected to examine the operations and hardware necessary for polar, equatorial, nearside, and farside exploration of the major terrain types on the Moon. A phased approach of both building up capabilities and learning how to explore the Moon as well as sequentially visit these regions is depicted in Figure I. The architecture phases considered in the GPoD are:

- Polar Exploration & System Validation
- Polar Relocatability
- Non-Polar Relocatability
- Long Duration

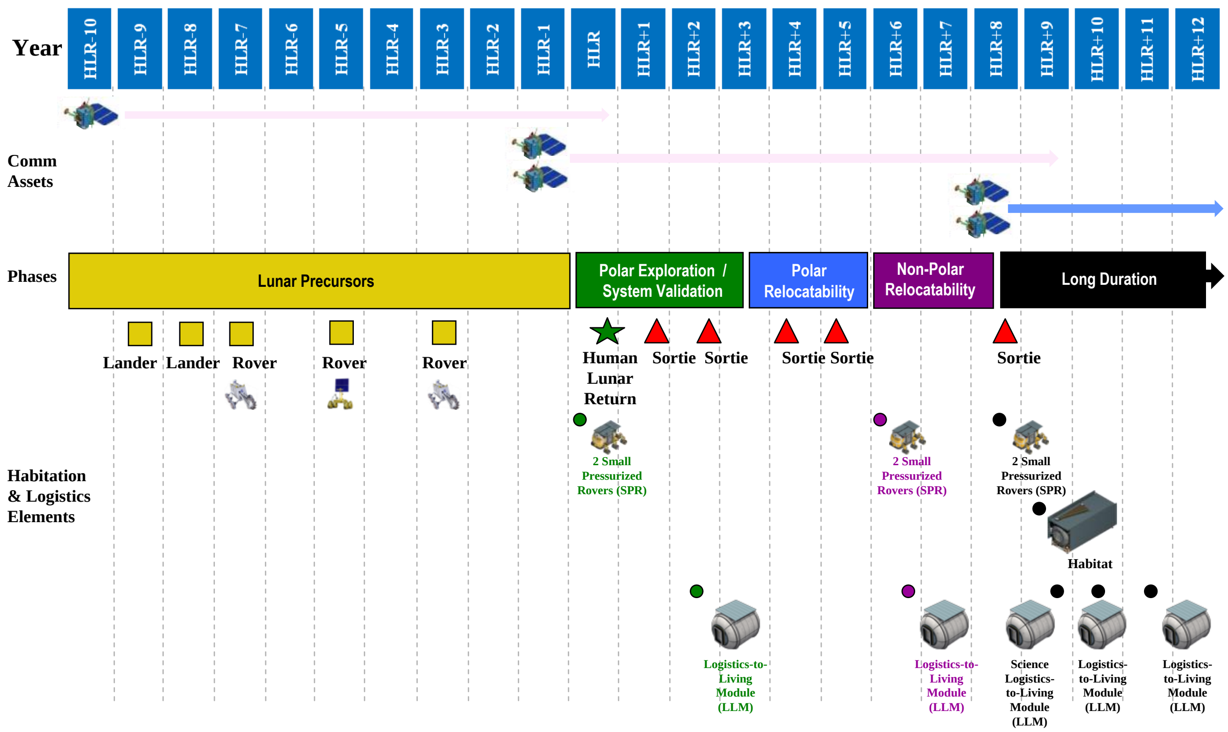

Figure I. Global Point of Departure Mission Phases

III. APPROACH TO INCORPORATING ISRU INTO LUNAR CAMPAIGN

ISRU involves the extraction and processing of local resources, both natural and discarded, into useful products and services. In particular, the ability to extract and make propellants, life support consumables, fuel cell reagents, and radiation shielding can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. Also, the ability to modify the lunar landscape for safer landing, transfer of payloads from the lander to an outpost, mitigation of dust generation, and emplacement and build-up of surface infrastructure are also extremely important for long-term lunar exploration, science, and commercial operations. If considered properly, ISRU capabilities and elements can significantly change how other systems required for sustained human presence on the Moon are designed and integrated, potentially break our reliance on Earth supplied logistics, and promote the establishment of commercial space products and services. When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar exploration:

1. Lunar resource characterization and mapping for planning and science
2. In-situ production of mission critical consumables for crew, power, and transportation
3. Civil engineering and construction for hardware and crew protection and infrastructure growth
4. In-situ energy production and storage
5. In-situ manufacturing, repair, and reuse

For ISRU systems and capabilities to be effective, it requires the use and integration of multiple surface elements, such as mobility platforms, power systems, and gas and liquid storage elements. Also, since the purpose of ISRU systems and capabilities is to provide products and services for exploration, other surface elements that use these products and services need to be designed to take advantage of this from the start, even if the products and services are not available right away. Table I below lists the major tasks and activities associated with the 5 main areas of ISRU and what purpose each serves.

Table I. ISRU Main Areas, Functions, and Purpose

	ISRU Tasks & Activities	Purpose
1	*Resource Prospecting/Mapping*	*Measure and map potential resources for site selection and ISRU planning; Opportunistic Science*
1a	Chemical/Mineral Characterization & Mapping	Measure and map regolith geotechnical and mineral/chemical attributes of surface regolith and subsurface down to 0.5 m to select feedstock for ISRU functions (supports lunar science objectives)
1b	Hydrogen/Water/Volatile Characterization & Mapping in/near Permanently-shadowed Craters	Measure and map geotechnical and hydrogen/water volatiles down to 1 meter to assess potential for large scale extraction (supports lunar science objectives)
1c	Solar Wind Volatile Characterization in Regolith and Pyroclastic Glasses	Measure solar wind volatile concentrations in surface regolith (especially high titanium mare) and pyroclastic glass material (supports lunar science objectives)
2	*Consumable Production*	*Reduce Earth delivery logistics; Enable new exploration*
2a	Oxygen Extraction from Regolith	Produce oxygen for crew, EVA, and propulsion
2b	Water/Hydrogen/Helium Scavenging from Altair Lander	Convert residual propellants into water; Produce water with excess hydrogen and In-situ oxygen; Scavenge helium pressurant from tanks
2c	Solar Wind Volatile Extraction from Regolith	Extract and separate hydrogen, nitrogen, helium, carbon, etc. from regolith
2d	Water/Hydrogen/Volatile Extractrion from Permanently-shadowed Crater Regolith	Extract and separate hydrogen, water, ammonia, methane, hydrogen cyanide, etc. from regolith
2e	Methane/Carbon Dioxide Production From Trash/Crew Waste Processing	Process trash and crew waste to produce methane and carbon dioxide
2f	Metal/Silicon Extraction from Regolith for Manufacturing	Produce silicon, iron, aluminum, etc from regolith as feedstock for in-situ manufacturing
2g	Cement and Modified Regolith for Construction	Produce feedstock from construction thru modification of bulk regolith
2h	Plant/Fish/Livestock Growth Support	Provide infrastructure and feedstock to support plant growth and fish/livestock food production.
3	*Civil Engineering & Construction*	*Reduce mission and crew risk; Enable infrastructure growth*
3a	Excavate and transport regolith for consumable production (2a, 2b, 2c, 2d, 2f, & 2g)	Provide regolith for in-situ processing
3b	Construct Landing Pads & Roads (clear areas, berms, sintering)	Protect hardware from plume damage; Mitigate dust around surface infrastructure
3c	Utilize regolith for Radiation Protection (burial or covering)	Bury/cover habitats to protect crew from solar/galactic radiation; Bury/cover nuclear reactors with regolith
3d	Construct Structures from In-situ Materials	Modify regolith and construct structures for hardware protection and crew
4	*Energy Production and Storage*	*Reduce mission risk; Enable infrastructure growth*
4a	Construct Thermal Energy Storage from In-Situ Materials	Modify regolith for use as thermal storage media for energy storage and generation
4b	Construct Solar Arrays from In-Situ Materials	Modify regolith and fabricate solar arrays on lunar surface for power generation growth
5	*Manufacturing & Reuse*	*Reduce Earth delivery logistics; Reduce mission risk*
5a	Hardware Scavenging and Recycling	Remove fluid and electrical components from dead landers and infrastructure for reuse (modularity required)
5b	Rapid Prototype Part Fabrication	Produce spare parts from powdered metals and plastics

III.I Examination of Impact of ISRU Incorporation

The main emphasis of incorporating ISRU as part of the ISECG Reference Lunar Architecture is to enable long-term exploration sustainability while supporting the goals of 'Extreme Mobility', Mars Forward , and enable significant science in an 'opportunistic way'. Because ISRU hardware has never been flown and operated in space, full implementation of ISRU capabilities from the start was deemed too risky by mission planners. Therefore, the ISRU Function Team used the following approach that would allow ISRU capabilities deployed to provide benefits to the reference lunar architecture while minimizing the risk to the mission with incorporation of ISRU.

Identify limitations to the architecture scenarios under consideration which ISRU can help solve

Because of potential limitations with launch vehicles and landers, payload delivery to the lunar surface and the return sample payload from the lunar surface may be constrained. This will have the effect of requiring more missions, shorter stay times, and/or prioritizing and eliminating exploration or science hardware from the mission. All of these lower the 'payback' for exploration and science for the cost spent. Other potential limitations in early crewed missions to the Moon include: establishing sufficient power assets to cover solar eclipse periods, consumables for crew surface stay time and extending the range of surface mobility, and global lunar surface access with complete crews and payloads.

Identify high risk and mass reduction candidates for ISRU capabilities

Reducing and eliminating consumable delivery from Earth, minimizing damage to deployed hardware and science equipment due to lunar dust and landing plume debris, and reduce radiation hazards to crew are areas where ISRU capabilities can provide significant benefits to human lunar mission plans. For sustained operations, the ability to recover from failures through in-situ repair and fabrication of replacement parts can also provide significant reductions in mission cost and risk.

<u>Identify ISRU applications that support long-term 'Sustainability' goals</u>

Once ISRU capabilities have been adequately demonstrated, their products and services can take on greater roles in sustaining on-going activities and to enable new exploration capabilities. For example, producing propellants and reusing space transportation elements for sample return, crew ascent/descent, and hopping to other locations are enabled with ISRU. ISRU can also establish long-term surface exploration sustainability through repair and manufacturing, production of in-situ energy (thermal and electrical) capabilities, and construction of habitats and structures. All of these can lead to the establishment of commercial providers for ISRU products and services. It is important that commonality, modularity, and interoperability of hardware and interfaces for ISRU and other surface elements be considered from the start to obtain the maximum benefit for these sustainability efforts.

<u>Identify ISRU processes and applications for Mars Forward scenarios</u>

It is important to recognize that one of the main goals for human lunar exploration is to prepare for Mars and outer solar system exploration. Therefore, every effort should be made to find common technologies, hardware, and operations between lunar and Mars exploration architectures. With respect to Mars ISRU, oxygen production for ascent propulsion is mission enabling for human Mars exploration. Even though this oxygen will come from the atmosphere instead of the soil, the ability to produce, liquefy, store, and transfer propellants remotely are important operations that can be demonstrated on the Moon to reduce Mars mission risk. However, the search for water and the ability to extract and process water from Mars surface soil could significantly enhance Mars mission capabilities. Processes associated with solar wind and polar water/ice volatile characterization and extraction, as well as the hydrogen reduction of regolith process on the Moon, are very synergistic with Mars surface water characterization and extraction from Mars soil. The ability to use lunar propellants for surface hopping or establishing ISRU waystations to extend surface exploration capabilities could also be utilized on Mars to significantly improve science and exploration capabilities. Since a Mars sample return mission that utilizes in-situ produced propellants is often considered a necessary ISRU validation precursor before human missions to Mars, the ability and capabilities to make and transfer propellants and return samples to Earth from the lunar surface can serve as a stepping stone to Mars exploration while potentially enabling common technologies and systems to perform both lunar and Mars robotic exploration missions thereby reducing development costs.

Based on using this approach to evaluating how ISRU capabilities can best support the reference lunar architecture, it was determined that the primary benefits of incorporating ISRU capabilities into the human lunar exploration architecture are:

- Reduce or eliminate the need to deliver oxygen, water, fuel cell reactants, and propellants from Earth; thereby lowering cost or increasing delivery of science or exploration hardware.
- Reduce mission and crew risk through increased radiation protection, dust and landing plume mitigation, and landing hazard reduction through manipulation of lunar surfaces and regolith.
- Provide a backup to Earth delivered systems in case of failure and long term expansion of these capabilities especially for life support, power, and habitation.
- Provide enhanced or new capabilities over Earth delivered systems, such as lander reuse or ISRU fuelled sample return

<u>III.II Mission Drivers for ISRU Incorporation and System Design</u>

For ISRU to be beneficial, the mass and cost of launching ISRU capabilities (and associated power and robotic systems) must be less than the product or service that the ISRU systems would provide. Mission drivers for evaluating how beneficial incorporation of ISRU systems into the ISECG Reference Lunar Architecture are the following.

<u>Mass of life support consumables (and tanks) delivered from Earth</u>

The amount of life support consumables required is a function of crew surface stay time,

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the number of crew, the degree of life support system closure, and the number of Extra Vehicular Activities (EVAs) planned. Because full implementation of life support systems was delayed until the Long Duration phase of the reference human lunar architecture, life support consumables and tankage need to be delivered from Earth in the Polar Exploration and System Validation , Polar Relocatability, and Non-polar Relocatability phases. It was determined that the mass of the delivered consumables and tankage in these early mission phases equalled or exceeded the mass of the ISRU plant, rover, and power system required to produce the oxygen need to support the missions planned. Should the ISRU systems be relocatable, systems deployed during the System Validation phase could be used during the Polar Relocatability phase as well providing further mission benefits.

Ability to obtain water from Altair lander residual propellants

For mission assurance, propellant reserves are manifested to ensure the crew lands safely. Also, all propulsion systems carry ‘unusable’ propellant at the bottom of propellant tanks and in the pipes to the thrusters and engines (called residuals). The oxygen and hydrogen propellant reserves and residuals are ‘in-situ’ resources that can be converted into water upon landing. Since the Altair lander propulsion system operates at an oxygen-to-hydrogen mixture ratio of <6:1, excess hydrogen will remain after all of the oxygen has been consumed. This excess hydrogen, if reacted with in-situ produced lunar oxygen can almost double the amount of water produced. However, for water to be scavenged from the Altair lander, a capture system must be attached shortly after landing (or preinstalled) with adequate tank volume to capture the water produced.

Mass of radiation shielding delivered from Earth

The mass of radiation shielding delivered from Earth is based on crew surface stay time, allowable radiation dosage, and mission risk. The need to support Extreme Mobility makes the use of lunar regolith as a radiation shield difficult and possibly impractical for crew mobility. Also, long duration surface stays will expose astronauts to large amounts of Galactic Cosmic Radiation (GCR) and potentially solar flares which will require large amounts of shielding. In-situ production of water (through lander residual propellant scavenging with in-situ oxygen or polar water) and/or processed trash may be needed for mobile and long-duration stay radiation protection.

Amount of time allowed for ISRU operations before crew use

The amount of time between crewed missions is a main driver for ISRU system size and power requirements. Since only one or two crewed missions are planned per year, 6 to 12 months may be available to produce needed mission consumables before the crew leaves Earth. The longer amount of time available for production operations, the lower the production rate needed; thereby reducing ISRU system mass and power needs. Also, by producing consumables before the crew departs Earth, mission risk is minimized, since the crew will know the consumables are present before leaving Earth.

Duration of eclipse periods

The duration of eclipse periods has three impacts on lunar ISRU systems. One, it influences the amount of time allowed for ISRU operations before crew use, thereby effecting production rate and operation power requirements. Two, it influences the power system mass required to keep the ISRU system safe during eclipse periods. Three, it influences the ISRU system design and selection based on start-up and shutdown transient effects. Long eclipse periods at lunar equatorial sites favor selection of ISRU systems that can be started and shutdown easily; therefore molten electrolysis might not be selected unless nuclear power was available for continuous operation.

ISRU system life, maintenance, and spare part requirements

ISRU operations will mostly be performed when the crew is not present, and may be pre-deployed before crew activities even start. ISRU systems must also operate for long periods of time in dusty/abrasive environments to minimize system mass and power requirements. Therefore, system reliability will be important with the minimum of maintenance required. Commonality of critical systems, such as water electrolysis and oxygen storage, with other surface systems such as fuel cell power and life support may be important to minimize spare part logistics and increase overall mission reliability and flexibility.

Architecture payload capability to lunar surface

The amount of payload that can be delivered to the lunar surface in crew and cargo vehicles is a key aspect of what can be accomplished in human lunar architectures. Limited delivery capabilities require pre-deployment of logistics and hardware before crew arrives. If pre-deployment is required, delivery of ISRU capabilities over Earth delivered consumables would enable increased science and exploration over time.

Because ISRU hardware has never been flown and operated in space, the approach to incorporating ISRU into the lunar architecture is to first demonstrate, than perform pilot operations, before full implementation. This allows early lunar missions not to relying on ISRU capabilities for mission success, but encourages surface systems to be flexible enough to incorporate ISRU capabilities once they have been adequately demonstrated. With respect to ISRU incorporation into the lunar architecture, there are two driving factors to consider: what ISRU capabilities need to be adequately demonstrated before they are utilized in a mission critical role, and not all ISRU capabilities are needed at once, but are linked to growth and evolution of other surface system elements and architecture goals. While early human lunar exploration missions may not *require* ISRU for mission success (Apollo missions were successful without ISRU), performing early ISRU demonstrations and pilot operations can reduce the risk and cost of long-duration human exploration, and potentially reduce consumable logistics deliveries from Earth in subsequent missions if successful. The approach the ISRU Function Team recommended for incorporation of ISRU advocated a three phased approach:

<u>III.III Phased Approach to ISRU Incorporation</u>

i) *Demonstrate the feasibility of the ISRU function or application* – perform subscale proof-of-concept demos.
ii) *Deploy Pilot operations to provide benefits* - provide products and services to enhance or extend mission capabilities and/or reduce mission risk above Earth-delivered assets and logistics, while at the same time verifying production rates, reliability, and long-term operations before full implementation begins.
iii) *Institute full implementation of ISRU functions or applications when verified* – incorporate ISRU in mission critical roles and include industry to allow for an on-ramp of commercial products and services.

Figure II below provides a graphical representation of how each ISRU implementation phase may affect Earth supplied logistics and mission criticality, and at what point in lunar mission plans each phase occurs.

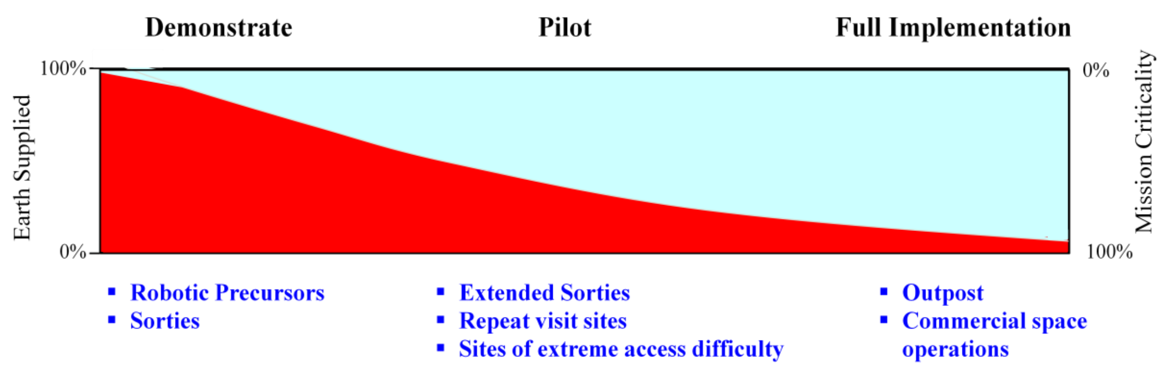

Figure II. ISRU Architecture Incorporation Approach

IV. AREAS OF ISRU DEVELOPMENT INTEREST BY AGENCIES

Each space agency that participated in the ISRU Function team began with different levels of understanding and hardware experience. Since the US National Aeronautics and Space Administration (NASA) has been actively pursuing the development of lunar ISRU technologies and systems since 2005, it had the greatest depth of understanding and involvement, however, the Canadian Space Agency (CSA), European Space Agency (ESA), Italian Space Agency (ASI), Japanese Aerospace Exploration Agency (JAXA), and UK Space Agency (formally the British National Space Center) all had performed lunar ISRU studies and hardware development to varying degrees.

Since 2005, NASA has focused on the first 3 of the 5 main areas of ISRU relevant to human lunar exploration: Lunar resource characterization and mapping for planning and science; In-situ production of mission critical consumables for crew, power, and transportation; and Civil engineering and construction for hardware and crew protection and infrastructure growth. NASA has performed architecture and system studies involving oxygen extraction from regolith and lander propellant scavenging. In particular, NASA has developed technologies and systems for lunar polar volatile/ice characterization, lunar regolith excavation and delivery, regolith processing preparation (beneficiation and size sorting), extraction of oxygen from lunar regolith (hydrogen reduction, carbothermal reduction, and molten electrolysis), and area-clearing/surface sintering[2]. NASA has also performed low-g regolith behaviour testing, lunar regolith simulant development, and laboratory and field testing of technologies and complete systems.

The CSA has focused on the first and third main areas of lunar ISRU; Lunar resource characterization and mapping for planning and science; and Civil engineering and construction for hardware and crew protection and infrastructure growth. The CSA has performed architecture and system studies involving mobility platforms for science, ISRU, and crew lunar activities, performed technology and system development in mobile platforms, excavating, and area clearing, and has initiated development of drills, manipulators/arms, and support equipment for resource characterization and science activities. The CSA has also developed lunar regolith simulants, and performed laboratory and field testing of technologies and complete systems.

The ESA, ASI, and UK Space Agency have focused primarily on oxygen extraction from regolith for lunar ISRU development. The ESA and ASI has studied oxygen extraction from regolith techniques and has shown interest in developing technologies associated with the carbothermal reduction method of oxygen extraction. The ASI has several areas of interest in the framework of the ISRU paradigm that are currently under investigation through specific research projects including the *study* of a high mobility lunar surface vehicle based on the ASI program "Italian Vision for Moon Exploration". In particular, the COmbustion Synthesis under MIcrogravity Condition or COSMIC project, whose main contractor is the University of Cagliari, Dipartimento di Ingegneria Chimica e Materiali, is aimed also to exploit the use of self-propagating high-temperature reactions to develop new technologies for manned space exploration"

The UK Space Agency has focused on a molten salt approach of oxygen extraction. While similar to the molten electrolysis work currently funded by NASA, molten salt electrolysis utilizes a calcium chloride salt to reduce the temperature of the extraction process by several hundred degrees centigrade. However, a salt recovery step is required for batch operations.

V. DESCRIPTION OF ISRU ELEMENTS UNDER CONSIDERATION

To determine what ISRU elements should be incorporated into the ISECG Reference Lunar Architecture, the ISRU Function Team examined the possible ISRU Tasks and Activities in Table I with respect to the mission benefits, risks, and drivers associated with incorporation of ISRU, and the importance and time phasing of these ISRU capabilities into architecture plans. Based on this evaluation and work with the Campaign Integration Team, the following ISRU capabilities and elements were incorporated into the ISECG Reference Lunar Architecture.

V.I The Ability to Make Oxygen and Water for Crew and Fuel Cell Power (Functions 2a-2d & 3a)

To support Extreme Mobility and extensive Extra Vehicular Activity (EVA) operations before lunar habitats are established with life support systems that allow significant closure of the air/water loops, significant quantities of life support, EVA, and power system consumables must be brought from Earth or durations for crewed surface exploration must be severely constrained. The ability to scavenge water and residual hydrogen from the Altair lander after landing and extract oxygen and volatiles from the lunar regolith could provide significant benefits early in lunar architecture plans if adequately developed and demonstrated. ISECG Reference Lunar Architecture ISRU elements with these capabilities are described below. Some of these elements are associated with the ISRU Function Team while others are associated with the Mobility or Servicing Function Teams. However, all elements are required to provide the service and products desired for lunar architecture.

ISRU Demo Plant

The Hydrogen (H_2) Reduction Demonstration Plant element produces oxygen from lunar regolith by reacting H_2 gas with iron-oxide minerals at ~1000 C to make water. The water can be kept or electrolyzed to make oxygen (O_2) and recycle hydrogen for further processing. The element requires regolith to be delivered and removed using a separate rover/excavator (Terrain Management Vehicle). Size sorting and possibly mineral beneficiation (if technology is ready) will be used to increase performance of the Demo Plant by concentrating iron-oxide in the feedstock and increasing reaction kinetics. The ISRU Demo Plant element also includes a solar array based on the Portable Utility Pallet (PUP) design to provide power for processing, and an oxygen tank module to store oxygen produced in a liquid state at 150 psi. Design drivers are oxygen production rate required, iron-oxide concentration, and amount of solar energy available per year. The element is completely stationary so will need to be offloaded if the regolith delivery element cannot reach the regolith hopper and will need to be moved by another element during architecture element relocation.

The ISRU Demonstration Unit is sized to produce and store approximately 250 kg of oxygen per year. This is small enough to fit onto a small cargo lander with the necessary power and excavation elements while large enough to provide usable product quantities to benefit future crewed missions if successful. Figure III depicts a notional lander with ISRU demonstration package and an actual engineering breadboard of a hydrogen reduction system field tested in Hawaii in November, 2008. All elements associated with extracting and storing oxygen from lunar regolith are delivered in one cargo package. Operations are planned to start before the crew arrives. The O_2 is transferred to either the PUP or another element designed to connect to the ISRU storage tanks for usage by the crew. The plant's solar array system is designed to provide power during sunlight periods. Power for eclipse periods and when stowed for relocation must be provided by an external source.

ISRU Pilot Plant

The ISRU Pilot Plant Element will utilize the Carbothermal Reduction process to produce oxygen from lunar regolith by reacting methane (CH_4) gas with silicate minerals at >1600 C to make carbon monoxide (CO). Hydrogen gas (H_2) is also released when methane cracks and is reacted with the CO in a catalytic reactor to produce CH_4 and water (H_2O). The water is electrolyzed to make oxygen (O_2) and recycle hydrogen for further methane reformation processing. The regolith is melted using a solar concentrator. The oxygen produced is stored in gaseous or liquid state in tank modules; liquid storage is assumed in the mass estimate. Design drivers are oxygen production rate required, silicate concentration, allowable methane/carbon loss, and amount of solar energy available per year. The element requires regolith to be delivered and removed using a separate Rover/excavator element and a separate electrical power supply for water electrolysis and oxygen storage operations and for eclipse period survival.

The ISRU Pilot Plant is sized to produce and store approximately 1000 kg of oxygen per year. The solar concentrator and water electrolysis subsystems may be used for other purposes including trash processing, water distillation, and fuel cell reactant regeneration. Figure IV depicts a carbothermal reduction system concept and an actual engineering breadboard of a carbothermal reduction system field tested in Hawaii in February, 2010. Regolith is delivered to the ISRU Pilot Plant using the same rover/excavator developed for the Demo Plant since the Pilot plant is at least 10 times more efficient in oxygen extraction, thereby reducing the amount of regolith required per kilogram of oxygen produced. Operations are planned to start before the crew arrives. The O_2 is transferred to either the PUP or another element designed to connect to the ISRU storage tanks for usage by the crew. Solar concentrators are used for regolith processing, but power for water electrolysis and oxygen liquefaction and storage is provided by another element; PUP or Power Supply Unit.

Rover/Excavator (Terrain Management Vehicle) [1]

The Terrain Management Vehicle (TMV) supports the ISRU demonstration element as well as providing basic functionality for regolith handling and raw material transportation on the lunar surface. Additional to its ISRU support function, the TMV provides means for site preparation, scouting, regolith excavation possibly combined with regolith analysis instruments, and general transportation of unpressurized goods or equipment. Primary Functions include: Robotic mobility, Regolith procurement, Transportation, Site preparation, and Waste disposal.

The element collects regolith through a bucket wheel excavator into a regolith container. It then delivers its payload to the ISRU element, where the container can be emptied into the system. Waste output from ISRU can be collected in the same container and are transported to a disposal site. The TMV is assumed to provide up to 250 kg/day of regolith to an ISRU element. Figure V depicts a rover/excavator system concept and actual engineering breadboard hardware developed by the Colorado School of Mines and Lockheed Martin.

Figure III. ISRU Demonstration Plant Concept & Field Tested Hardware

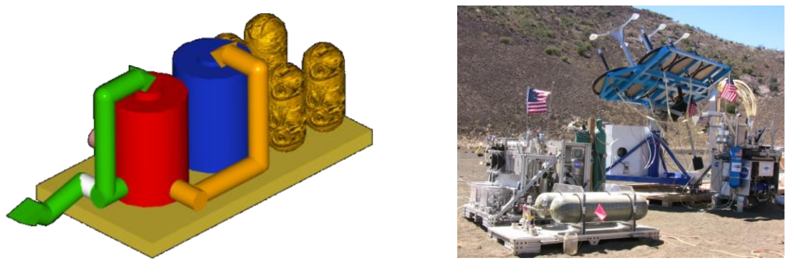

Figure IV. ISRU Carbothermal Reduction Pilot Concept & Field Tested Hardware

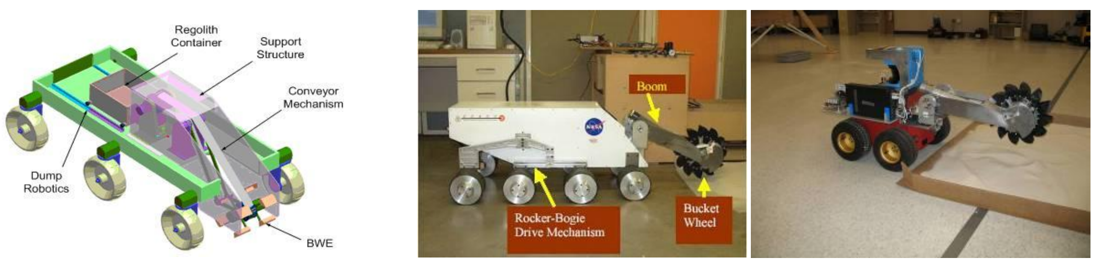

Figure V. Rover/Excavator Concept for ISRU Oxygen Production & Breadboard Hardware

V.II The Ability to Protect Crew & Hardware from Radiation, Dust, and Landing Plumes (Functions 2b, 3b, & 3c)

Examination of the damage to the Surveyor III by the Apollo 12 Lunar Module (LM) landing plume showed that even though the Surveyor lander was 160 to 180 meters away, the landing plume debris scoured surfaces, caused pits, and fractured paint. Modeling of the Apollo LM landing plume debris through examining videos and physics-based models predict that larger particles could have traveled 400 m/s up to 2 km/s, the landing plume hazards that might be caused by the new larger Altair lander could be 4 to 16 times greater than the Apollo LM at the same separation distance, and that greater distance will reduce but not eliminate the effects to surrounding hardware[3]. Since many lunar mission scenarios require hardware and logistics to be pre-deployed, unloaded, and tested before the crew arrive, the ability to create landing pads, berms, and harden surfaces to mitigate dust/plume generation could significantly reduce the risk of damage to critical hardware from subsequent lander missions to the same location. Crew protection from long-term radiation exposure can also benefit from these ISRU capabilities as well as in-situ extraction and production of water.

For the ISECG Reference Lunar Architecture, the hardware associated with providing crew and hardware protection, through the manipulation of lunar regolith, is incorporated into the Mobility Chassis Toolkit (MCT) and/or the Terrain Management Vehicle. The MCT is a collection of tools designed to attach to a mobility chassis for use around the outpost, to include ISRU, site preparation and setup, limited cargo handling, vehicle recovery, and other tasks. Figure VI depicts NASA and Canadian Space Agency (CSA) rovers with area clearing/berm building capabilities demonstrated in field tests in 2008 and 2010.


Figure VI. Area Clearing Systems Field Tested by NASA and CSA

V.III The Ability to Locate, Characterize, and Map Lunar Resources (Functions 1a, 1b, & 1c)

For ISRU to be as efficient as possible, understanding where the highest concentrations of minerals and volatiles of interest are located, understanding the geotechnical and bulk characteristics of the regolith, and understanding the terrain to position ISRU hardware and plan delivery routes is extremely important. Therefore, at a minimum terrain visualization and mapping, geotechnical property, and mineral composition instruments should be deployed on either a dedicated rover or on the excavation rover used to support ISRU operations so only a single mobile platform is needed. Besides supporting ISRU, these terrain and resource mapping activities should have close ties to lunar science objectives providing 'opportunistic science'. For missions close to the lunar poles, joint science and exploration 'ground truth' missions to search for and characterize hydrogen/ice signatures from Clementine, Lunar Prospector, and the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) missions should be pursued. ISECG Reference Lunar Architecture elements with resource and terrain mapping capabilities are the RAPIER and Selene X class rovers.

RAPIER[1]

The RAPIER is a lightweight rover supporting a "plug-and-play" reconfigurable chassis. It is a small autonomous robotic rover capable of travelling tens of kilometers, with built-in provisions for communication, power variable autonomy tele-operation guidance and navigation. It can serve as a robotic surveyor during precursor missions for the selection of optimal landing sites prior to human arrival, perform site surveys, environment assessments and resource explorations. Additionally, the rover could perform autonomous environmental assessment of the sites to determine the hazards that future astronauts may encounter. This may include an autonomous patrol route that will provide multi-day assessments with one mobile resource. To meet precursor mission objectives, the rover will support modular science instruments that can be mounted on the chassis and plugged into power and data interface cables. The payload deck provides interfaces for up to six payloads, each having a footprint of up to 0.35 m x 0.3 m. A small manipulator is proposed as a baseline payload and occupies one of the interface locations. For lunar precursor missions, RAPIER will navigate and self-guide to interesting sites, cover a large area and gather science data to create global maps of the lunar surface to identify its morphology, topography and chemical composition.

SELENE-X[1]

The SELENE-X Class Rover is a rover of the JAXA SELENE Series which will be developed in late 2010s, as planned for Japan's participation in Human Lunar Activity. Upon landing on the lunar surface, the rover will self deploy from the lander and begin initial check-out activities. Tasks that the rover will take part in before human lunar return include, but are not limited to, the following: Site survey within a specified distance from the lander; Visit geological locations and dig holes to collect subsurface samples; Collect rocks on the lunar surface and grind them for analysis; Off-load instruments from the lander and install them on the lunar surface; and Provide descent imagery of other cargo and human landers.

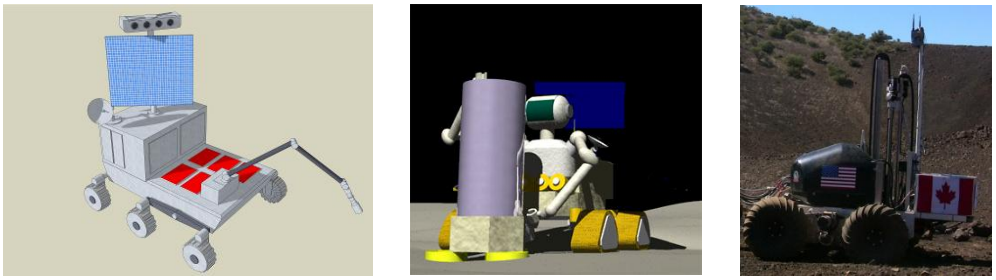

Figure VII. RAPIER and SELENE-X Concept Rovers and Breadboard Hardware Field Tested by NASA & CSA

VI. INTERNATIONAL COLLABORATION, ANALOGUE FIELD TESTING, AND POSSIBLE ROBOTIC PRECURSOR OPPORTUNITES

To minimize technology and flight system development costs, it is important that international partners collaborate early on areas of critical interest to minimize duplication and ensure technologies and interfaces are compatible. As stated previously, ISRU capabilities involve multiple technical discipline elements, such as mobility, regolith manipulation, regolith processing, reagent processing, product storage and delivery, power, manufacturing, etc. Also, for ISRU to be effective and beneficial, other surface elements and systems must be designed from the start to utilize ISRU products and services. Therefore, there are three levels by which international space agencies can work together on the development and deployment of ISRU systems:

i. Develop ISRU technologies and subsystems that can be incorporated into the other partner's ISRU module
ii. Develop complementary ISRU modules or lunar surface element modules that interact with ISRU modules
iii. Develop and establish infrastructure to support ISRU development

Which level of coordination international space agencies decide to pursue will be based on technology and system areas of interest and funding availability for each ISRU function or application of primary interest for lunar exploration.

ISRU Technologies and Subsystems Level Coordination

ISRU applications require an array of technologies and subsystems to be integrated together to successfully produce the desired product or service. Figure VIII depicts the subsystems associated with one concept for a Carbothermal Reduction from Regolith system. For ISRU system development within NASA, decisions are made as to whether components, subsystems, and systems are developed in-house or by industry/academia, and whether NASA or industry will serve as the system integrator. These decisions can be expanded to include international space agencies (or their funded industry and academia partners) and could serve as a provider of critical technologies and subsystems for NASA-led integrated systems or vice versa. This level of coordination (at the technology and subsystem level) requires the greatest level of integration between partners since complete system operations are not possible until all the technologies, components, and subsystems have been successfully integrated. This level of coordination may also require the least investment since the cost to develop an individual technology or subsystem is much less than that associated with developing, integrating, and testing a complete ISRU system. The partnership between NASA and CSA on the development and testing of the Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) system and sample acquisition device is an example of this level of coordination. CSA co-funded drill and sample acquisition development and later provided a TriDAR drilling site selection camera for integrated RESOLVE testing.

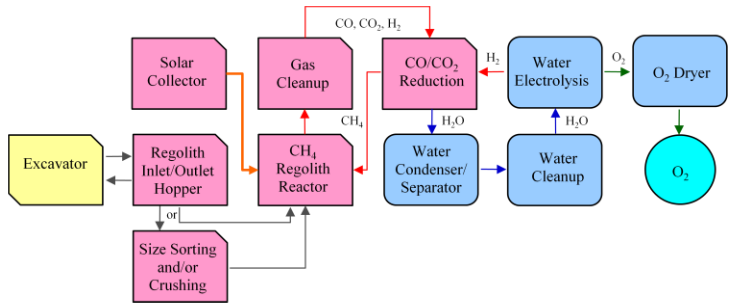

Figure VIII. Carbothermal Reduction System

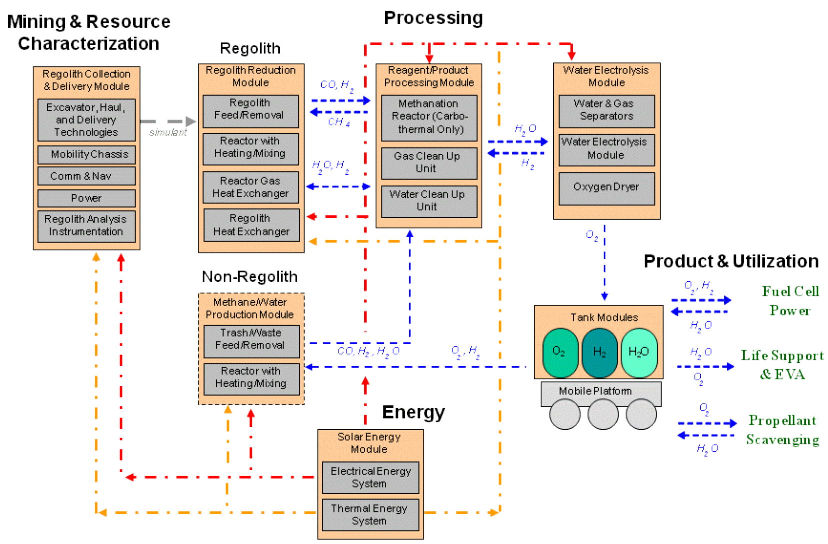

Figure IX. End-to-End Oxygen Extraction from Regolith System Modules

Develop complimentary ISRU modules or lunar surface element modules that interact with ISRU modules

For ISRU to be successful, multiple modules and elements need to interact with other lunar surface system elements to achieve the desired end-to-end mission capability. ISRU hardware and systems must interact with habitat, life support, power, mobility, and communications systems. Also, there are different methods to perform the same task or function that are complementary (ex. Hydrogen Reduction vs Carbothermal Reduction for oxygen extraction from regolith). Figure IX depicts the major modules and subsystems required for completing the task of extracting and storing oxygen from lunar regolith. Since each of the modules are discrete, international partners can allocate authority or responsibility for each module depending on the level of interest and available funding. The level of coordination required for integration at the Module level is much simpler than at the Technology and Component level, but again, interfaces and operations between the elements must be clearly defined. Another approach for coordination at the Module level is to have partners provide upgrades and enhancements in efficiency and production rate in an evolutionary manner. For example, an upgraded regolith processing module (molten salt vs hydrogen reduction) or water electrolysis module (higher production rate, outlet pressure, and/or electrical efficiency) could be swapped in the system at a later date by one of the partners.

Develop and establish infrastructure to support ISRU development

Processing in-situ resources (whether natural or discarded materials/trash) on the Moon requires energy. One way to mitigate the amount of energy required is to process resources over as much time as possible. This introduces several difficulties and risks that need to be addressed including operating at 1/6 gravity in a vacuum for months to years through numerous thermal cycles. Also, lunar regolith is highly abrasive and non-homogeneous in minerals, contaminants, and particle sizes/shapes across the lunar surface. Earth-based testing will require the development of lunar simulants and infrastructure to perform 1/6 gravity and long-duration

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thermal/vacuum testing with lunar simulants to support development of ISRU technologies and systems for eventual operation on the lunar surface. Besides performance and life testing, integrated testing under simulated mission operation scenarios requires analogue sites with representative terrain and surface materials that can be used to support ISRU processes. Since ISRU systems often deal with hazardous materials and reactants (such as hydrogen, oxygen, and methane), test facilities and chambers must be designed to operate with appropriate hazard mitigation strategies. NASA and CSA have invest in the development of a Lunar Highland Type physical and mineral simulants and NASA has identified but not started modification of a vacuum chamber to support lunar surface and ISRU hardware environmental testing. NASA and CSA are also using Mauna Kea on Hawaii as a site for analogue field testing but are open to other sites if terrain and test support infrastructure are favorable. Coordinating and sharing resources in developing and operating lunar development infrastructure and analogue field tests is beneficial, and has been demonstrated by NASA and CSA in two successive analogue field tests in 2008 and 2010.

Analogue Field Testing of ISRU and Surface System Technologies and Systems

As stated previously, ISRU is considered a risk to mission success by architecture and mission planners since it has not been adequately demonstrated. To begin to overcome this concern, in 2008 ISRU developers initiated a new approach to developing and demonstrating ISRU capabilities; analogue field testing. An 'analogue' is a facility or place that simulates one or more aspects of the location of exploration of interest. Analogues can range from fixed-based environmental chambers to natural or man-made earth-based terrain settings. For ISRU, an analogue field site needs to simulate terrain, minerals, and physical attributes of surface soils/regolith. Over the last several years, NASA and CSA have utilized analogue field tests to both evaluate lunar architecture mission concepts with real hardware (versus analyses or computer simulations) and test new mission scenarios to influence lunar architecture development. For ISRU, analogue field tests could be used to build confidence in ISRU capabilities and products for mission planners and other system developers as well as begin to address the challenges of ISRU development and incorporation into missions by performing the following:

- Demonstrating and developing standard interfaces and products with other exploration surface and transportation elements
- Demonstrating and evaluating ISRU concepts under applicable conditions
- Evaluating ISRU system operations and procedures
- Demonstrating the feasibility and maturing ISRU hardware and operations at a relevant scale for mission applications

Two major ISRU-related analogue field tests have been performed to date by NASA and CSA; November 2008 and January/February 2010 on Mauna Kea in Hawaii[4]. The purpose of the first complete ISRU System Analogue Field Test was to (i) perform the first end-to-end test of excavation, oxygen production, and product storage in an integrated system configuration at a relevant scale for future human lunar missions, and (ii) demonstrate prototype hardware and operations associated with mobile resource prospecting to demonstrate the feasibility for a future lunar polar mission. Three major ISRU systems were developed by NASA for the analogue field test; a roving lunar polar resource characterization system called RESOLVE/Scarab, and two hydrogen reduction from regolith systems called ROxygen and PILOT. The CSA provided support to the RESOLVE/Scarab system for sample acquisition, drill site selection, and nighttime navigation as well as providing on-site and satellite communication between Hawaii and the mainland for the complete analogue field test. The German Space Agency (DLR) also participated in the field test by testing their lunar mole prototypes.

Because of the tremendous success of the first analogue field test with respect to the hardware, the integration, and the partnership with other international space agencies, it was decided during the field test that a second analogue field test would be pursued and led by the CSA. The purpose of the second ISRU and Lunar Surface Operations analogue field test would be to: (i) Advance ISRU hardware and systems demonstrated over 1st analog field test (using the ISRU 'mining' cycle), (ii) Expand ISRU system/capability integration with other transportation and surface elements (such as power and propulsion) and science activities, and (iii) Increase the scope and criticality of international partner involvement in ISRU development and demonstration.

The second lunar analogue field test was performed in January and February of 2010 at the same location on Mauna Kea in Hawaii as the first field test, and involved an upgraded RESOLVE lunar polar resource characterization package on a CSA provided rover, and an integrated carbothermal reduction of regolith production system with solar

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concentrators, water electrolysis, liquid oxygen storage, and liquid oxygen/methane thruster. The NASA ISRU hardware was powered by a CSA provided fuel cell. The CSA also demonstrated autonomous landing pad, road, and berm building capabilities. Because all aspects of ISRU and lunar surface system integration were tested in an end-to-end manor, the demonstration was referred to as 'Dust to Thrust'[4].

Besides providing tremendous technical and programmatic benefits, analogue field testing provides further benefits and opportunities to participants by developing engineers, encouraging interactions and building trust between surface and transportation system developers, developing international partnerships and data exchange agreements, and performing outreach and public education.

Based on work performed with the International Space Exploration Coordination Group (ISECG) for the Global Point of Departure (GPoD) lunar architecture, future ISRU-Surface Operation analogue field tests may also take on a larger role in performing mission simulations for robotic precursor and infrastructure establishment before crew arrive. Three major precursor missions that might be simulated include:

- Resource prospecting and terrain mapping to understand resources available and begin infrastructure and surface operation planning.
- Pre-deployment of ISRU systems with support hardware to begin production of mission consumables.
- Establishment of power, consumable, and civil engineering infrastructure before crew arrive.

Lunar Robotic ISRU Precursor Missions

There are six major reasons to perform lunar robotic precursor missions: Demonstrate long-term operations and environmental impacts of mission critical hardware; Reduce the risk of incorporating high pay-off ('game changing') technologies and systems; Evaluate potential sites of human exploration; Obtain early design and flight experience for human mission activities; Demonstrate 'Mars Forward' capabilities; and Increase public awareness and engagement in human exploration of space. Lunar ISRU can be considered a game changing technology since it strongly impacts the designs and requirements of transportation and other lunar surface system elements, and has the potential to significantly reduce the mass, cost, and risk for human lunar exploration. To demonstrate that ISRU can meet mission needs and to increase confidence in incorporating ISRU capabilities into mission architectures, terrestrial laboratory and analogue field testing along with robotic precursor missions may be required. A stepwise approach with international collaboration is recommended. The first step is to understand the resources available through orbital and surface exploration missions. Resources of particular interest are hydrogen, hydroxyl, water, and other polar volatile resources recently measured by Chandrayaan, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). The second step is to demonstrate critical aspects of ISRU systems to prove ISRU is feasible under lunar environmental and resource conditions (ex. subscale oxygen extraction from regolith). The third step is to perform integrated missions with ISRU and other connected systems, such as power, consumable storage, surface mobility, and life support at a relevant mission scale to demonstrate ISRU capabilities as well as the critical interfaces with other exploration systems. If possible, the mission should demonstrate the use of ISRU products (ex. in a rocket engine or fuel cell). This 'dress rehearsal' mission would be the final step before full implementation of ISRU into human missions, and may be performed during human lunar exploration activities (see ISRU Demo Plant). This stepwise approach is the most conservative approach, and may only be possible with international cooperation due to the limited number of robotic missions each nation/space agency can perform within their budget.

The Robotic Precursor Phase of the ISECG human lunar architecture is designed to improve the programmatic sustainability of the overall campaign by assuring early knowledge acquisition and early engagement with international partners, as well as other stakeholders including the science community and the public. Lunar Precursor missions represent a phased approach to development and testing to facilitate advancement of a human lunar campaign and other space exploration objectives. Primary objectives for robotic precursor missions include polar and non-polar lunar environmental characterization, resource prospecting, materials testing, technology development, component and system testing, and operations verification . The precursor missions also provide an opportunity to deploy operational infrastructure, conduct science that may yield particular value prior to the human campaign, establish and test procedures for collaboration among international partners, and provide opportunities for interactive public engagement in real time. Knowledge obtained as a result of these activities is used for informing future exploration site selection, improving safety, and reducing the cost and risk of the baseline ISECG human lunar architecture. Figure X. represents a notional robotic precursor phase before human lunar exploration begins. Time sequencing of the precursor missions is to allow information and lessons-learned to flow into subsequent human mission elements[1]. ISRU-related objectives are incorporated into the 3rd and 5th robotic mission, and include resource characterization and terrain mapping and possibly subscale oxygen extraction from regolith demonstrations. A dedicated mission to examine lunar polar volatiles and water/ice has been considered, but is not currently shown in the plan.

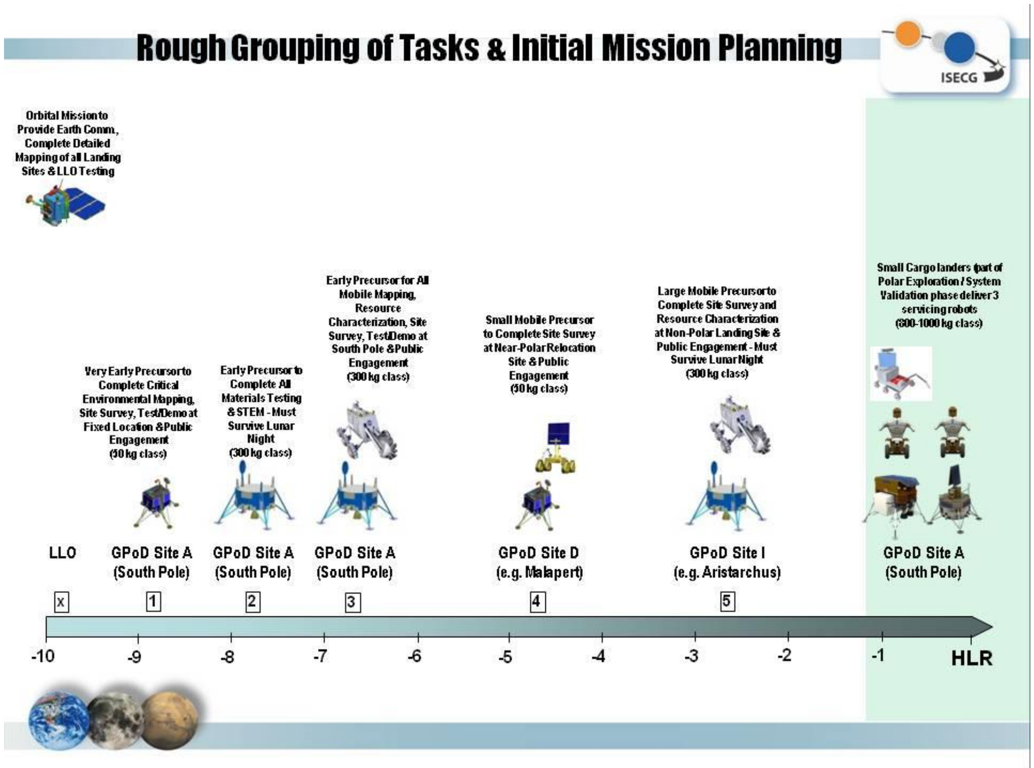

Figure X. Notional ISECG Robotic Precursor Plan

VII. SUMMARY

The International Space Exploration Coordination Group (ISECG) Reference Lunar Architecture provided the first opportunity for representatives from international space agencies to work closely together on requirements, concepts, and systems toward the goal of exploring the Moon with humans. Because ISRU has never been flown before and knowledge of ISRU capabilities and concepts were new to many of the participants, many ISRU functions and benefits were left out in this first reference human lunar architecture. However, the ability to make oxygen and water for crew and power, the ability to protect crew and hardware from radiation and damage, and the ability to locate and characterize lunar resources were capabilities that were identified and incorporated into the reference lunar architecture. The ISRU Functional Team devised a logical and phased approach to incorporate these capabilities into the reference lunar architecture that provided early benefits with the minimum of mission risk. Because ISRU capabilities require the use and integration of multiple surface elements, several methods for international collaboration were identified. In particular, joint development and testing of technologies and systems under analogue field test conditions was highlighted based on several years of effort between the NASA and the CSA. Hardware, experience, and teamwork developed through analogue field tests can provide the basis for subsequent lunar robotic precursor missions before crewed missions begin.

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