A Robust and Affordable Lunar Exploration Program Based on Lunar Resource Development

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Agenda

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Objectives of Architecture

- **Conduct lunar robotic missions to demonstrate key technologies and operations**
- **Emplace initial production facilities robotically**
- **Build a robust lunar infrastructure, suitable for supporting a 4 person crew for extended durations (1 year or more) at a single (equatorial) location**
  - Habitat sized for twice the maximum number of crew members
  - Include backup, fully fueled lunar transfer vehicles in space and on the lunar surface
  - Build reservoirs of life support consumables
  - Power-rich
- **Develop the capability for significant production of power systems, life support systems and habitats using lunar materials**
- **Over about 6 years in which human missions are carried out, develop lunar infrastructure to allow sustainable lunar operations in parallel with a Mars exploration program**
  - Potential for international or commercial lunar base operations

Overview of Architecture

- **Robotic Demonstration Phase**
  - A series of small robotic missions, launched with Delta II – Medium - class expendable launch vehicles, demonstrates several key technologies
- **Oxygen Production Plants**
  - Delivered to the Moon on automated missions, launched with Intermediate-class launch vehicles
- ***Human and cargo missions***
  - Launched with the expendable launch vehicles with capacity of 30 mt to LEO

ISRU Capabilities Developed

- ***Burial of inflatable structures, for radiation shielding***
- **Oxygen derived from lunar iron-rich regolith**
  - Support transportation system between the Moon and an Earth-Moon L1 transfer node
- ***Solar wind hydrogen derived from lunar regolith***
  - Support launches from the Moon
  - Nitrogen for the life support system is a byproduct
- ***Solar photovoltaic arrays made predominantly from lunar materials***
  - Provide a growing power production capability
  - Includes glass, aluminum and silicon solar cell production
- ***Glass and ceramics for structural applications***
- ***Much of the material needed to construct habitats and greenhouses from lunar regolith materials***

Architectural Strategy

- ***Establish fully radiation-shielded inflatable habitats before first humans arrive to support long duration stays***
- ***Utilize lunar oxygen to fuel spacecraft going to Moon at L1, coming from the Moon on the Moon***
  - Reusable robotic tanker transfers propellant from Moon to L1
  - All human vehicles are expended at the end of their use (typically, they go from L1 to Moon to Earth)
    - Reusable lunar vehicle for L1 to Moon to L1 is introduced when confidence has been built; reduces number of ELV launches required to support a human mission
    - Number of reuses does not have to be large (e.g. 3 per unit) to significantly reduce costs
- ***CEV used for transfer of crews from Earth to L1***
- ***Lunar-produced photovoltaic arrays contribute to a power-rich environment***
- ***Hydrogen is produced only when sufficient power has been developed from lunar-produced photovoltaic arrays***
  - Addition of lunar hydrogen increases useful payload that can be delivered to the Moon
- ***Closed life support system in lunar greenhouse***
- ***Production of other products (metals, structural materials, ceramics, glass) from lunar materials allows cargo flights from Earth to bring higher-valued materials***
  - Utilitarian objects – tools, utensils, furniture, etc. can be made on Moon

Mission Sequence

- ***A notional sequence of emplacement of infrastructure and human exploration missions has been constructed***
- ***The scale of the missions has been verified approximately using scaling models developed by Colorado School of Mines (needs testing)***
  - Models include ISRU production facilities, major hardware items, transportation vehicles
  - Real designs are needed for most of these elements
- ***Details of the payloads to be delivered to the lunar surface, including needs for operational replenishment of supplies, need further development***
- ***Assumes a standard set of transportation systems***
  - CEV for crew from Earth to L-1
  - Orbital transfer vehicle of same scale as CEV for cargo to L1
  - Human lunar lander , initially expendable, ultimately reusable for L1-Moon-L1
  - Reusable cargo lander
  - Reusable lunar propellant tanker
  - I-ELV available for small payloads and resupply

Proposed Mission Sequence: Robotic Preparation Missions

Year	Launch Vehicle	Surface payload (kg)	Mission objective
2012	M-ELV	~200	Demonstrate oxygen production, transfer, storage using lunar materials
2013	M-ELV	~200	Demonstrate large scale excavation & technique of habitat coverage with regolith
2014	M-ELV	~200	Demonstrate solar photovoltaic array production based on lunar materials
2015	M-ELV	~200	Demonstrate metal and glass production
2016	I-ELV	~1000	Pilot O_2 plant (15 mt O_2 / yr.)
2017	H-ELV	~5000	Deliver lunar tanker
2017	I-ELV	~1000	2nd O_2 plant (15 m. O_2 / yr.)

M-ELV – Medium ELV (existing); I-ELV – Intermediate ELV (existing)

Initial Base Sequence

Year	Launch Vehicle	Surface payload (kg)	Mission objective
2018	H-ELV	6-7 mt	Deliver cargo lander
2018	H-ELV	6-7 mt	Deliver and bury inflatable habitat (8 people); deliver and test nuclear power plant (100 kWe)
2018	H-ELV	6-7 mt	Deliver cargo lander (reusable)
2018	H-ELV	6-7 mt	Deliver first lunar solar cell production facility (200 kW/yr); Deliver elements of power management and distribution system
2019	H-ELV	6-7 mt	Deliver spare lunar lander
2019	H-ELV	6-7 mt	First human mission – 28 days on surface
2020	H-ELV	6-7 mt	Deliver H_2 production facility (6 mt H_2 / yr + 48 mt O_2 / yr)
2020	H-ELV	6-7 mt	Second human mission – 90 days on surface
2021	H-ELV	6-7 mt	Add habitat infrastructure – ISRU production capabilities – Extra lunar solar cell production facility (200 kW/yr)
2021	H-ELV	6-7 mt	Human mission - 180 days – science, technology testing

H-ELV – Heavy ELV – Nominal 25 – 30 mt to LEO

Growth Phase

Year	Launch Vehicle	Surface payload (kg)	Mission objective
2022	H-ELV	6-7 mt	Add habitat infrastructure– Greenhouse (8 people)
2022	H-ELV	6-7 mt	Human mission 1 year – science, technology testing
2023	H-ELV	6-7 mt	Add habitat infrastructure production – Expand metals production capabilities – Mars test bed activities
2023	H-ELV	6-7 mt	Human mission 1 year – science, technology testing
2024	H-ELV	6-7 mt	Add habitat infrastructure– Expand ceramics/glass -Fabricate O2 storage facilities
2024	H-ELV	6-7 mt	Human mission 1 year – science, technology testing, construct habitat/greenhouse with 95% lunar materials
2025-	Transition to Mars Program		

H-ELV – Heavy ELV – Nominal 25 – 30 mt to LEO

Model Results

Yr	Mission	Payload to Lunar Surface	IMLEO (kg)	Objective
2012	Oxygen production demonstration	200 kg robotic	11236	Demonstrate feasibility of O2 extraction, transfer and use
2013	Excavator demonstration	200 kg robotic	11236	coverage with regolith
2014	Solar Cell production	200 kg robotic	11236	Demonstrate in-situ production of solar cells; raw materials brought from Earth
2015	Metals production	200 kg robotic	11236	Demonstrate Fe, Si, Al production and preparation
2016	Pilot O2 plant	950 kg robotic	15056	Produce and store 15 mt oxygen in one year; integrated solar power system
2017	Reusable lunar tanker	5938 kg robotic	23154	Demonstrate round trip capability, L1 - Lunar Surface-L1; deliver 5 mt propellant to L1
2017	Additional O2 plant	950 kg robotic	15056	Add 15 mt/yr O2 production capacity and storage
2018	Lunar Transporter Predeployment	4158 kg robotic	18810	Deliver expendable cargo vehicle; load O2 at L1
2018	Habitat	6028 kg robotic	23374	Deliver habitat, excavation system, nuclear power plant (100 kW), load O2 at L1
2018	Lunar Transporter Predeployment	4158 kg robotic	18810	Deliver reusable cargo vehicle; load O2 at L1
2018	Emplace solar power system	7000 kg robotic	25800	and on Moon
2019	Deliver spare lunar lander	5322 kg robotic	21651	Deliver spare lunar lander to outpost; load with O2 for return
2019	Deliver lunar lander	6869 robotic	25427	Deliver lunar lander to outpost; load with O2 for return, deliver extra PMAD, food, EVA
2019	Human mission	6547 kg human	24641	the lander
2020	Deliver H2 plant	7000 kg robotic	25800	Combined H2/O2 plant, capable of producing 6 mT H2/yr, extra PMAD, food
2020	Deliver lunar lander	6869 robotic	25427	Deliver lunar lander to outpost; load with O2 for return, deliver extra PMAD, food, EVA
2020	Human mission	6547 kg human	24641	Human flight to outpost site ; 28 day mission; O2 and H2 loaded on Moon; O2 in L1; 4 people
2021	Add infrastructure	6944 kg robotic	25610	Add PMAD; additional solar cell production, glass plant
2021	Deliver lunar lander	6869 robotic	25427	Deliver lunar lander to outpost; load with O2 for return, deliver extra PMAD, food
2021	Human mission	6547 kg human	24641	Human flight to outpost site ; 180 day mission; O2/H2 loaded on Moon; O2 in L1
2022	Add habitat/infrastructure	6626 kg robotic	24833	Supply flight; additional infrastructure; greenhouse (8 people), consumibles
2022	Deliver lunar lander	4573 robotic	19823	Deliver lunar lander to outpost; load with O2 for return, food
2022	Human mission	6547 kg human	24641	Human flight to outpost site ; 1 year mission; science, maintenance, process development
2023	Add habitat/infrastructure	7000 kg robotic	25800	Deliver lunar lander to outpost; load with O2 for return, food, add non-metals and metals production and fabricati
2023	Human mission	6547 kg human	24641	1 year mission, Mars analog studies, science
2024	Add habitat/infrastructure	7000 kg robotic	25800	Fabricate O2 storage facilities
2024	Human mission	6547 kg human	24641	Fabricate greenhouse using 95% lunar materials

Comparison of ISRU Architecture to Other Architectures

- **Introduction of lunar propellants reduces scale of largest launch required from Earth to that of existing expendable launch vehicles**
- **Number of ELV launches per year is modest (4-5 in beginning, fewer in later years)**
  - Architecture not costed, but after 5 years, continuing support requires only 2 ELV launches from Earth for each human mission with new supplies and cargo
- **Reduced transportation costs allow resources to be spent on robustness**
  - Spare, fully fueled lunar landers are available both at L1 and on Moon
  - Growing water reservoir with time; no import of life support consumables when hydrogen is being produced on Moon
- **Compared to non-ISRU architectures, Initial Mass in LEO is about 1/3 of that required**

Other Potential Risk Reduction Approaches

- ***Landing with empty fuel tanks is a perceived risk of ISRU architectures that must refuel on Moon***
  - Increase redundancy of engines and avionics
    - Use of lunar propellant greatly increases design margins
- ***Expand surface navigation infrastructure***
  - Reduce position errors of landing
- ***Landing site preparation***
  - Diminish risk of mechanical problems landing reusable vehicles

Architecture Risk Mitigation

- **Oxygen production on the Moon doesn't work or requires substantially more mass**
  - Utilize pre-positioned propellant transported from Earth
    - Reduces effectiveness of architecture, but maintains scale of transportation system
- ***Hydrogen production from regolith is not feasible***
  - Transport hydrogen from Earth
  - Extract water from polar deposits and transport using surface transportation infrastructure
- ***Reusable transportation elements are too risky***
  - Utilize expendable elements
    - Reduces effectiveness of architecture

Technology Keys

- **Production of oxygen**
  - Several choices of processes available currently being investigated in ESRT program
  - Key technology: Reliable isolation of process from lunar environment (moving material in and out of reactor)
  - Key performance parameters: reliability, maintainability, continuous operation over long periods of time
- **Production of hydrogen**
  - Improved effectiveness of excavation/transport systems for large quantities of material
  - Reactor technology that diminishes residence time of regolith in reactor
  - Storage and handling of liquid hydrogen
- ***Other materials production technologies***
  - Long life
  - High reliability
  - Process improvements
- ***Reusable in-space transfer vehicles***
- ***Reliable, low-loss automated cryogen transfer on Moon and in space***
- ***Automated rendezvous and docking***