

# ISRU Development Roadmap

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**AIAA Space Resources Technical Committee**

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The Lunar Outpost and Beyond**  
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# Presentation Outline

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- ISRU Capabilities Required for Human Exploration of Space
  - Near-Term ISRU Capabilities
  - Longer-Term ISRU Capabilities
- Technology Options for Near-Term ISRU Capabilities
- Challenges in Developing Near-Term ISRU Technologies
- Research Needs for Near-Term ISRU Technologies
- A Potential Near-Term ISRU Development Roadmap

# ISRU Capabilities Required for Human Exploration

## **Near-Term Capability Requirements [Before 2020]**

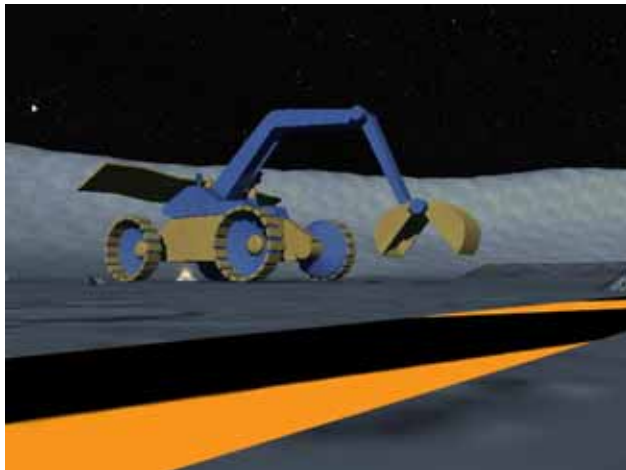
- Regolith excavation and transportation on the Moon (supports regolith collection and surface construction)
- Lunar regolith oxygen extraction, long-term storage, and distribution
- Resource and environment characterization in lunar polar regions (potential deposits of water ice and volatiles)
- Recovery of water/volatiles from lunar regolith (if resources are viable)

## **Longer-Term Capability Requirements [After 2020]**

- Regolith excavation and transportation on the Mars (supports regolith collection and surface construction)
- Mars water extraction from regolith
- Mars oxygen and propellant production
- Extraction of metals (including iron and silicon) from the regolith on the Moon and Mars
- Repair, fabrication and assembly of parts/products using in-situ resources to support self-sustained, long duration missions (Moon and Mars)
- Lunar in-situ power generation and storage



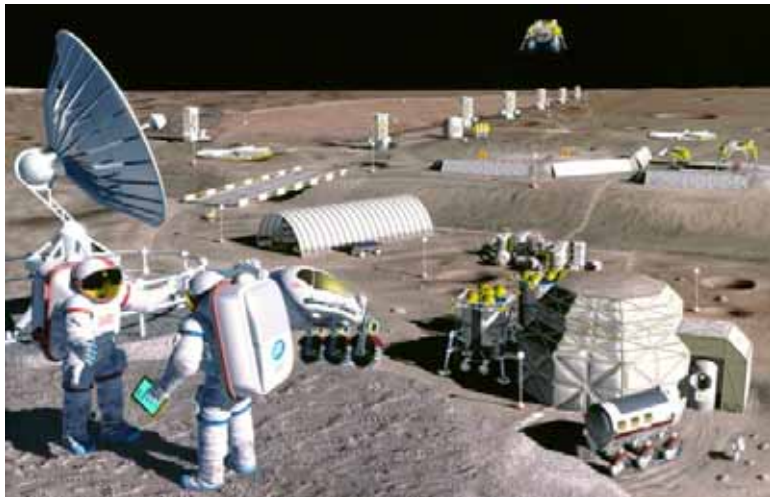
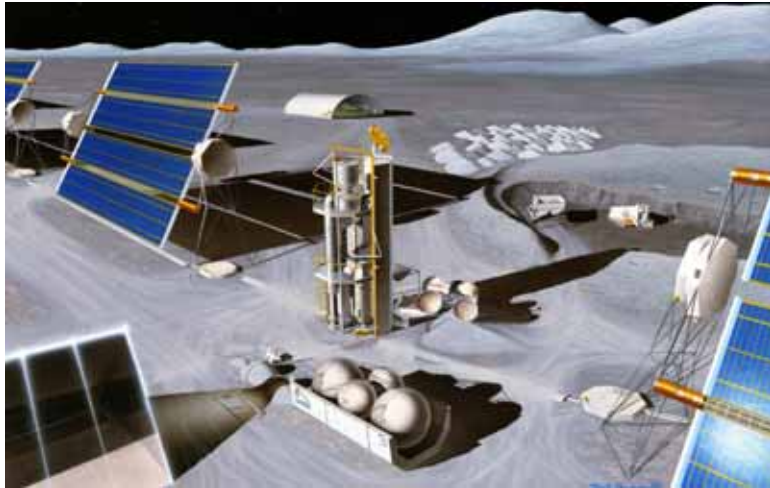
# Regolith Excavation on the Moon



*Image courtesy of Digitalspace*

- Dry regolith near the surface
  - Loosely consolidated material
  - Prototypes of numerous small excavator technologies have been built and tested in a laboratory environment (bucket wheel, bucket drum, bucket ladder, front end loader, scoop, etc.)
- Dry regolith located below the surface
  - More difficult to penetrate and excavate due to higher compaction
  - Some hardware has been built and tested, including Surveyor, Apollo and Viking missions
- Icy Regolith (Mars and potentially Lunar poles)
  - Can be very difficult to excavate if water content is moderate or high (behaves like a rock instead of a soil)
  - No hardware has been built and tested to excavate this material outside of drills and core sampling devices

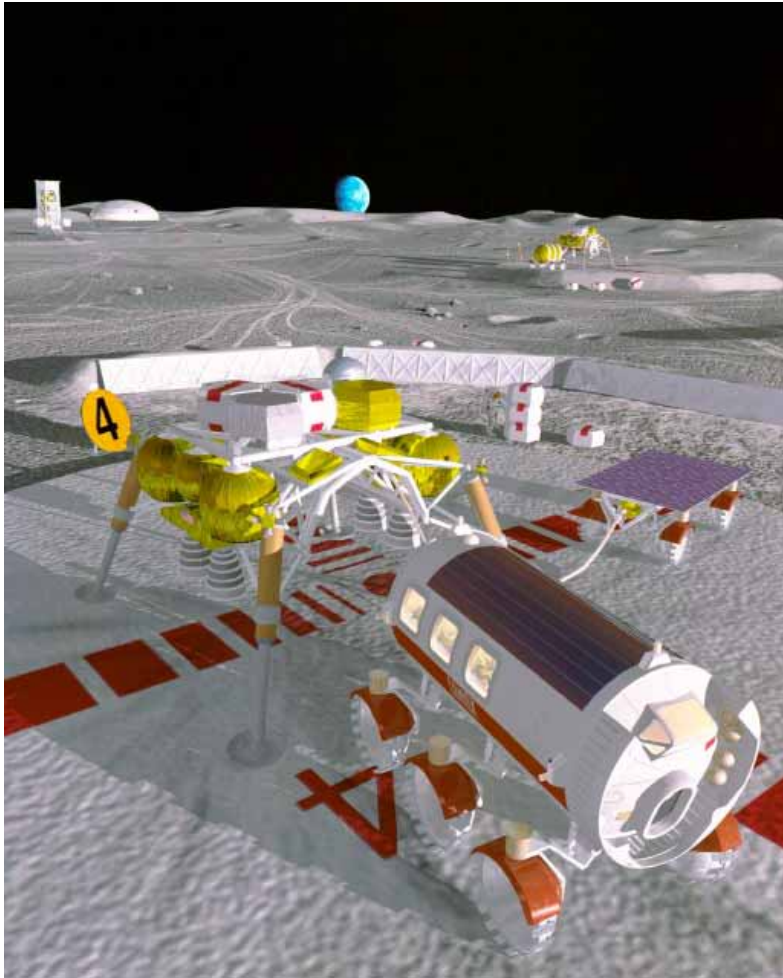
# Oxygen Extraction from Lunar Regolith



*Images courtesy of NASA*

- Numerous technologies have been demonstrated at a small scale in a laboratory environment to validate the basic extraction processes
  - Hydrogen reduction, carbothermal reduction, magma electrolysis, molten salt electrolysis, vacuum pyrolysis, etc.
- More work is needed to build and test end-to-end systems
  - Significant scale up is needed to produce usable quantities (at least 1 MT O<sub>2</sub>/year)
  - Valves, seals, regolith handling, and long-term oxygen storage have not been adequately developed

# Resource Characterization in Lunar Polar Regions



*Image courtesy of NASA*

- Ground truth is required to validate and characterize the resources at the lunar poles
  - Determine the form of the resources
  - Measure the amount and location of the resources
  - Characterize the local environment of the resources
- Resource availability could impact the site selection for a lunar outpost
- Even if significant resources exist in the permanently-shadowed regions, the local environment may be too challenging to efficiently recover them
- The current robotic missions (LRO and LCROSS) are not sufficient to establish ground truth

# Challenges in Developing Near-Term ISRU Technologies

- Transitioning lab-scale processes to extract oxygen from the lunar regolith to large-scale oxygen production plants that can operate in a closed-loop manner
- Day/night operations without continuous source of electrical/thermal energy
- Autonomous operation of systems
- Long-duration operation of systems with little or no maintenance
- Exposure to lunar regolith and dust
  - The lunar regolith (especially dust) is very abrasive and difficult to remove from surfaces
  - Exposure to regolith/dust will significantly shorten the operating life and reliability of valves, seals, bearings, joints, and other mechanical systems



# Challenges in Developing Near-Term ISRU Technologies

- Developing long-life components for regolith excavation
  - Highly abrasive nature of lunar regolith will accelerate wear on consumable parts in excavators and shorten operating times between maintenance
- Operating mechanical systems in permanently-shadowed polar regions
  - 40 K temperature, no light, and transportation in/out of craters
  - Nuclear power options would be very helpful in meeting some of these challenges
- Lack of mission opportunities to demonstrate key ISRU technologies on the lunar surface for risk reduction
  - Risk reduction activity is critical allow mission architects to include and leverage ISRU technologies



# Near-Term Research Needs on Earth

- Develop lunar dust tolerant valves, seals, bearings, and joints
- Develop regolith excavators that minimize or eliminate consumable parts that require Earth-supplied components
- Develop seals, bearings, joints, and other mechanical systems that can operate in a permanently-shadowed polar environment on the Moon
- Develop an end-to-end lunar regolith processing plant to produce 1 MT O<sub>2</sub>/year
  - Regolith collection and delivery to processing reactor
  - Production of oxygen in a closed-loop operation
  - Long-term storage and distribution of oxygen
  - Autonomous operation



# Near-Term Research Needs on the Lunar Surface

- Deploy and operate a small lunar regolith oxygen production plant (1 MT O<sub>2</sub>/year) on the surface of the Moon
  - Demonstrate regolith collection and delivery to processing reactor
  - Validate the performance of dust tolerant seals and valves
  - Demonstrate a closed-loop oxygen extraction process in the lunar environment
  - Demonstrate regolith, fluid, and gas handling in lunar gravity
  - Long-term storage and transfer of oxygen in the lunar environment
  - Demonstrate operation of equipment during multiple lunar day and night cycles
  - Demonstrate autonomous operation
  - Demonstrate closed loop operation of the overall system
- Many of these technologies will directly support other ISRU capabilities on the Moon and Mars



# Rationale for the ISRU Development Roadmap

- A meaningful ISRU Development Roadmap defines when key ISRU technologies need to be developed to meet the desired ISRU capabilities
- Although many ISRU capabilities and technologies would be beneficial in supporting near-term exploration needs, budgetary constraints require NASA to identify and focus on the most valuable ISRU capabilities and technologies
- The production of oxygen is widely regarded as the most valuable ISRU product, so that capability drives the near-term ISRU Development Roadmap
- Once lunar oxygen production has been validated on the surface of the Moon, it will open the door for many other ISRU capabilities and technologies to be demonstrated and implemented



# Near-Term ISRU Development Roadmap

- 2008 – Lab demonstration of at least one end-to-end oxygen production system to produce 1 MT O<sub>2</sub>/year from lunar regolith simulant (including surface regolith collection/beneficiation, processing reactor, oxygen extraction and long-term storage)
- 2009 – Field demonstration of at least one end-to-end oxygen production system from lunar regolith simulant to produce 1 MT O<sub>2</sub>/year
- 2009 – LRO and LCROSS missions to provide visual, topographic, and resource mapping data (may include evidence of lunar water ice)
- 2010 – Lab/field demonstration of an excavator in subsurface (compacted) regolith simulant/icy regolith simulant
- 2012 – Demonstrate autonomous operation of an end-to-end oxygen production plant from lunar regolith in a simulated lunar environment



# Near-Term ISRU Development Roadmap

- 2013 – Begin building small lunar regolith oxygen production plant (1 MT O<sub>2</sub>/year)
- 2015 – Demonstrate surface construction technologies using regolith (launch/landing area preparation, etc.)
- 2016 – Lander or rover mission to a permanently shadowed lunar polar location to establish ground truth for lunar water ice and characterize the resource
- 2018 – Small lunar regolith oxygen production plant (1 MT O<sub>2</sub>/year) is operational on lunar surface
- 2019 – Demonstrate an end-to-end oxygen/hydrogen production plant that utilizes lunar ice deposits (including icy regolith excavation, water extraction, water electrolysis, and O<sub>2</sub>/H<sub>2</sub> storage) in a simulated lunar environment
- 2020 – First human return mission to the Moon (additional short duration human missions continue for 5 years)



# Near-Term ISRU Development Roadmap

- 2020 – First human return mission to the Moon (additional short duration human missions continue for 5 years)
- 2020 – Begin to develop a large lunar regolith oxygen production plant (50 MT O<sub>2</sub>/year)
- 2025 – Missions to a permanently occupied lunar outpost missions begin with extended surface stays
- 2026 – Demonstrate in-situ manufacturing and repair technologies on the surface of the Moon
- 2030 - Large lunar regolith oxygen production plant (50 MT O<sub>2</sub>/year) is operational on the surface of the Moon
- 2030+ Demonstrate additional ISRU capabilities (fuel production, metals production, volatile gas extraction, helium-3, etc.)

# The Challenge

Stated goal of the Vision for Space Exploration

- Implement a sustained and affordable human and robotic program

“Incredibly expensive to get things to the surface”

Jeff Hanley - yesterday

**ISRU offers a unique capability to multiply the landed mass offering a truly sustainable approach**



# How to Realize the Potential

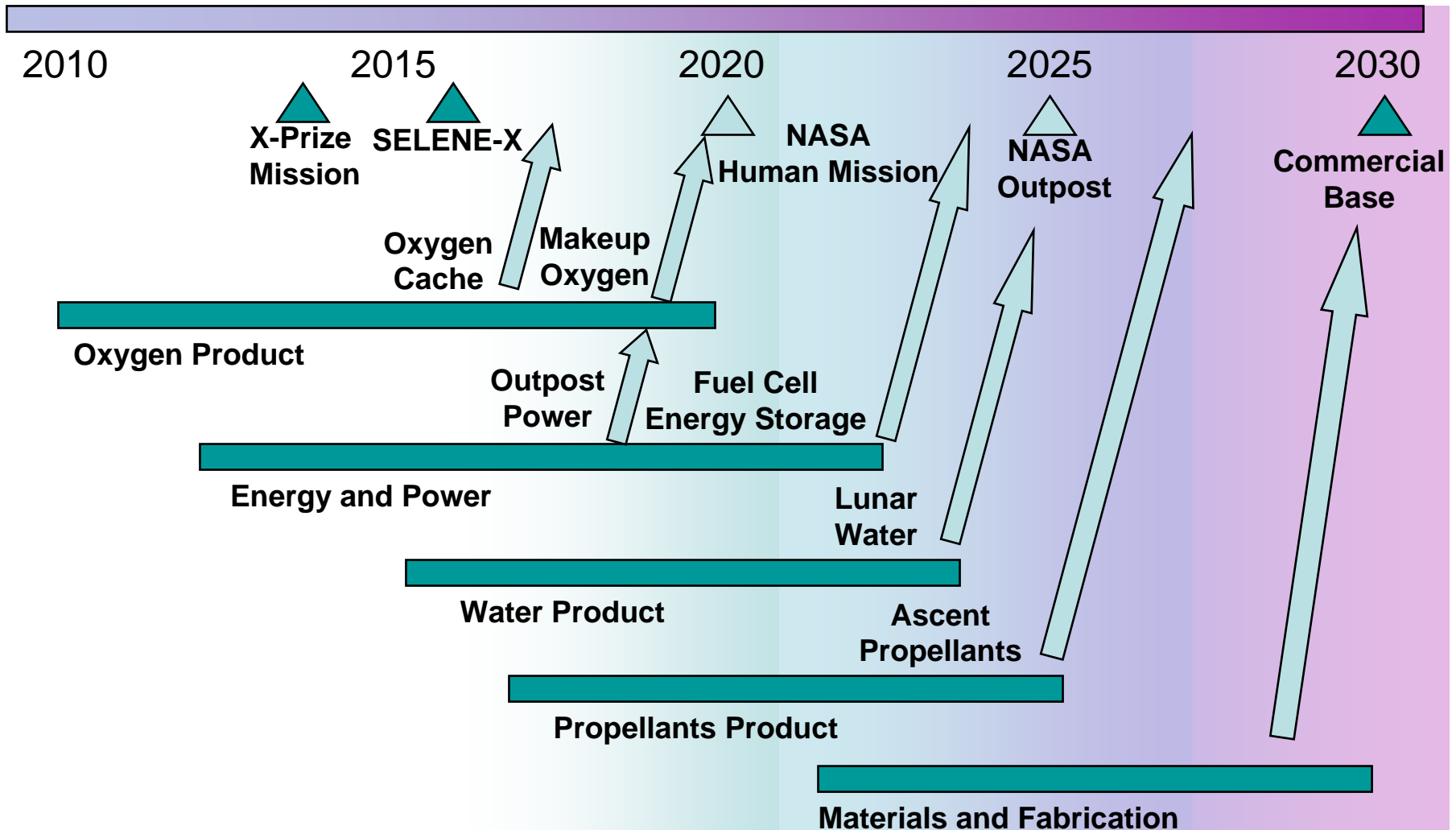
## - Without Breaking the Bank

- NASA should “buy” commodities
  - Oxygen
  - Water
  - Power
- Use COTS model
  - Buy lunar delivered product
  - Pay some up front development
  - Participate in the development

**A true commercial buy of ISRU products will reduce cost and an additional lunar mass delivery system will reduce system risk**



# Development Timeline



# Conclusions

- The ISRU Development Roadmap presented needs to be developed more fully
  - The AIAA Space resources Technical Committee continues to work with NASA, private industries and academia to support concepts and implementation
- This roadmap represents a relatively conservative plan to validate ISRU capabilities and adopt them into the NASA mission architecture
  - ISRU is not in the critical path of the near-term human exploration architecture, but it offers a plan to insert it in the future once it is validated in the lunar environment
- Early demonstrations and validations of ISRU technologies are needed to maximize the beneficial impact on the long-term human exploration program



# Acknowledgement

- A special thank you to numerous members of the AIAA Space Resource Utilization Technical Committee for reviewing this ISRU Development Roadmap and offering valuable inputs

