NASA IN-SITU RESOURCE UTILIZATION PROJECT—AND SEAL CHALLENGES

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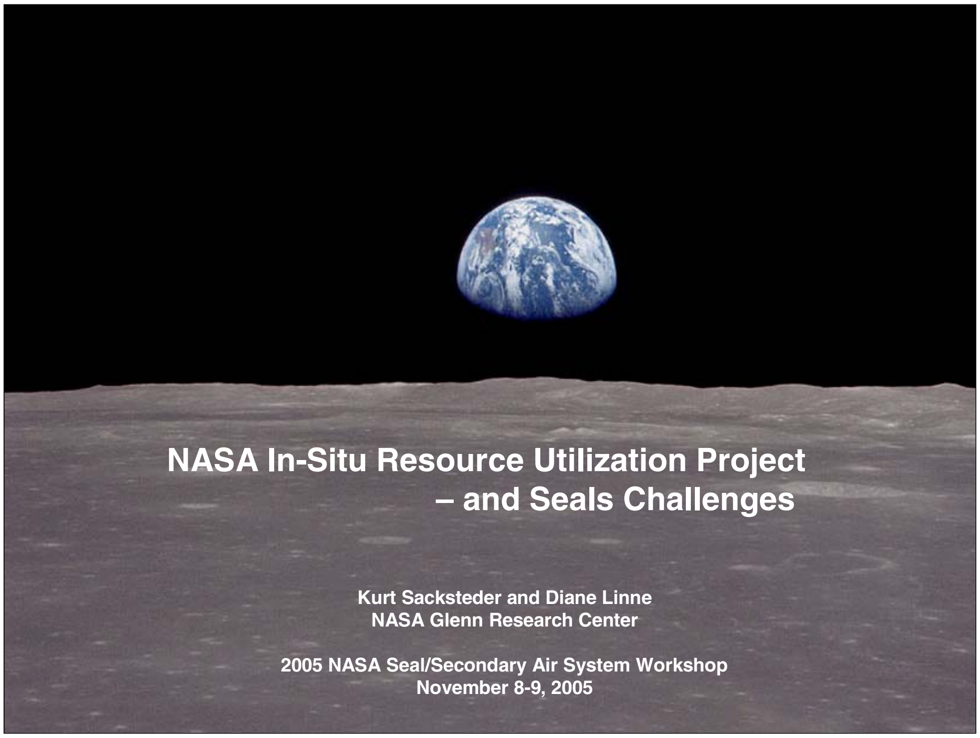
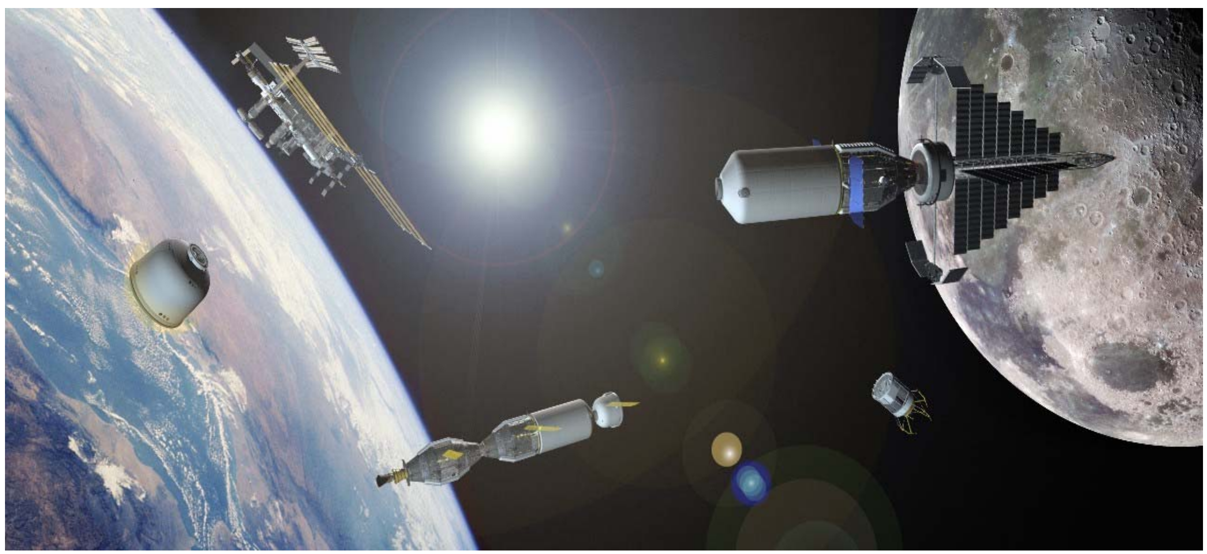


New Space Exploration Vision

- **On January 14, 2004, the President announced a new vision for NASA**
  - Implement a *sustained and affordable* human and robotic program to explore the solar system and beyond;
  - Extend *human presence* across the solar system, starting with a human return to the Moon in preparation for human exploration of Mars and other destinations;
  - Develop the *innovative technologies*, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  - Promote *international and commercial participation* in exploration to further U.S. scientific, security, and economic interests.



"Making use of the Moon's abundant resources…"

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What Are Space Resources?

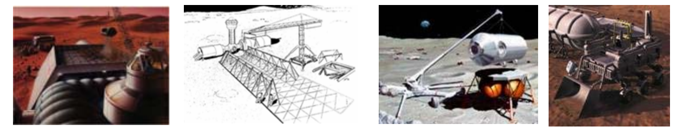
- **Traditional material resources including**:
  - Water from the soil or atmosphere
  - Atmospheric gases (CO_2, O_2, N_2, etc.)
  - Volatile species from the solar wind or comets (H_2, He, H_2O, CH_4, etc.)
  - Minerals/metals (Fe, Ti, Ni, Si, etc.)
- **Energy**
  - (Near) Continuous sunlight for electrical/thermal power and stable thermal control
  - (Near) Continuous Darkness for cryogenic fluid storage, scientific instruments and stable thermal control
- **Environment**
  - Vacuum/Dryness
  - Micro/Partial Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations for Earth/Sun/deep-space observations, mission staging
  - Isolation from Earth's electromagnetic noise, storage of duplicate vital information
  - Isolation for Earth to conduct hazardous testing (nuclear, biological, etc.) and extraterrestrial sample curation & analysis, etc.

In-Situ Resource Utilization exploits these resources, creating products & services that significantly reduce the mass, cost, & risk of extended-duration space exploration

Space Resource Utilization for Exploration

Mission Consumable Production

- ➢ **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- ➢ **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- ➢ **Life support consumables** (oxygen, water, buffer gases)
- ▪ Gases for science equipment and drilling
- ▪ Bio-support products (soil, fertilizers, etc.)
- ▪ Feedstock for in-situ manufacturing & surface construction



Surface Construction

- ➢ **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, plates, water, hydrocarbons, etc.)
- ➢ **Landing pad clearance**, site preparation, roads, etc.
- ▪ Shielding from micro-meteoroid and landing/ascent plume debris
- ▪ Habitat and equipment protection

Manufacturing w/ Space Resources

- ➢ **Spare parts manufacturing**
- ▪ Locally integrated systems & components (especially for increasing resource processing capabilities)
- ▪ High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

Space Utilities & Power

- ➢ **Storage & distribution of mission consumables**
- ▪ Thermal energy storage & use
- ➢ **Solar energy** (PV, concentrators, rectennas)
- ➢ **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

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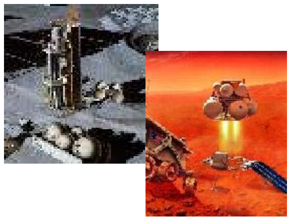
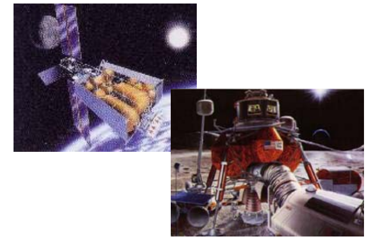
ISRU Enables Affordable, Sustainable & Flexible Exploration



Mass Reduction

Propellant Production
- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

Cost Reduction



- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

Space Resource Utilization

Risk Reduction & Flexibility

- Fewer Earth launches & reduced mission operations
- Reduced dependence on Earth
- Common hardware & mission consumables
- In-situ fabrication of spare parts for sustainable self-sufficiency
- Dissimilar redundancy
- Radiation & Plume Shielding

Enables Space Commercialization

- Material handling and processing technologies
- Infrastructure for space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Lunar Surface

Expands Human Presence

- Increase surface mobility and extend missions
- Habitat & infrastructure construction
- Consumables for propellant, life support, power, etc.
- Substitute infrastructure cargo for Earth-source propellant & consumables

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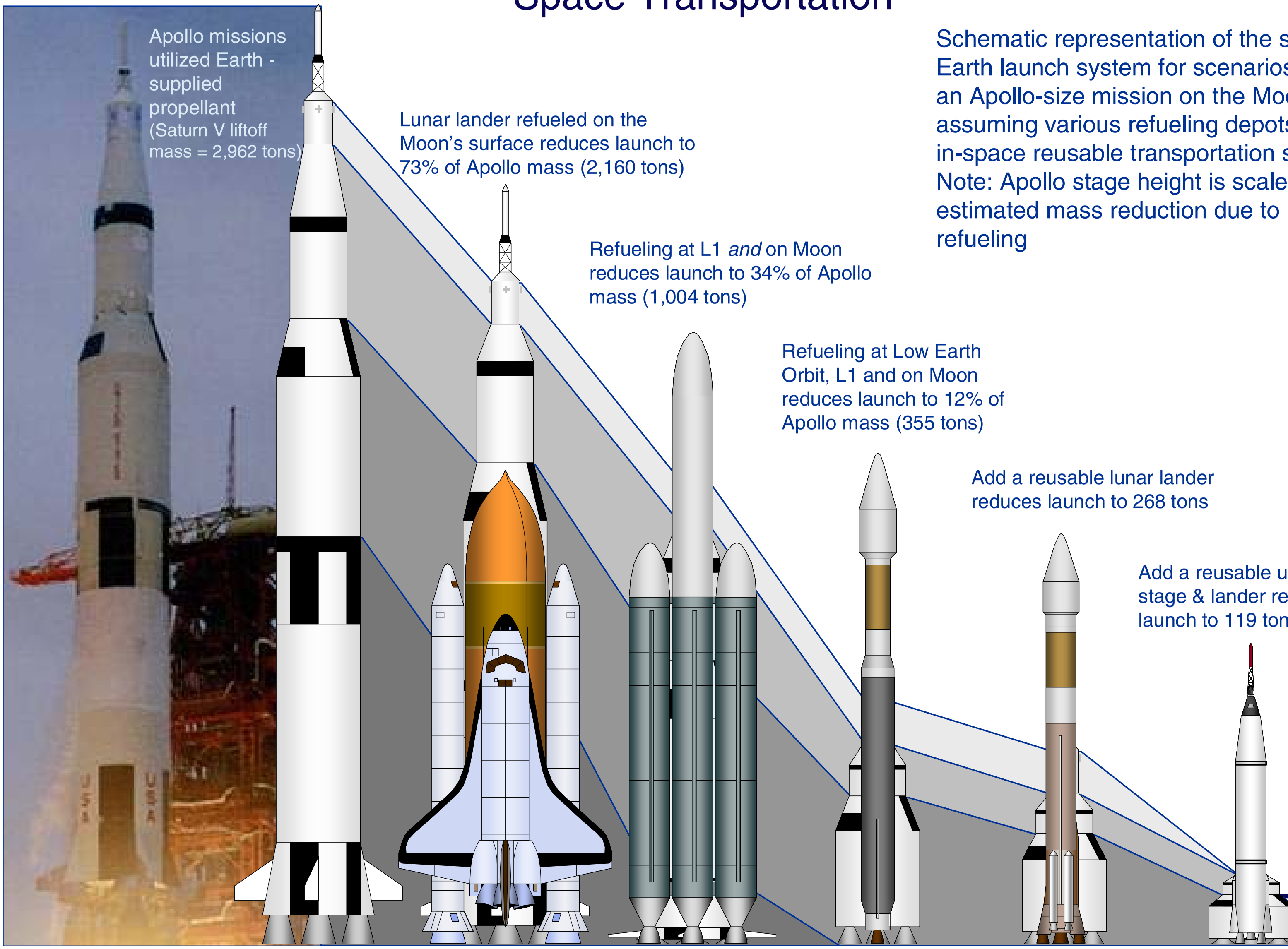
Propellant from the Moon Could Revolutionize Space Transportation

Schematic representation of the scale of an Earth launch system for scenarios to land an Apollo-size mission on the Moon, assuming various refueling depots and an in-space reusable transportation system. Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling



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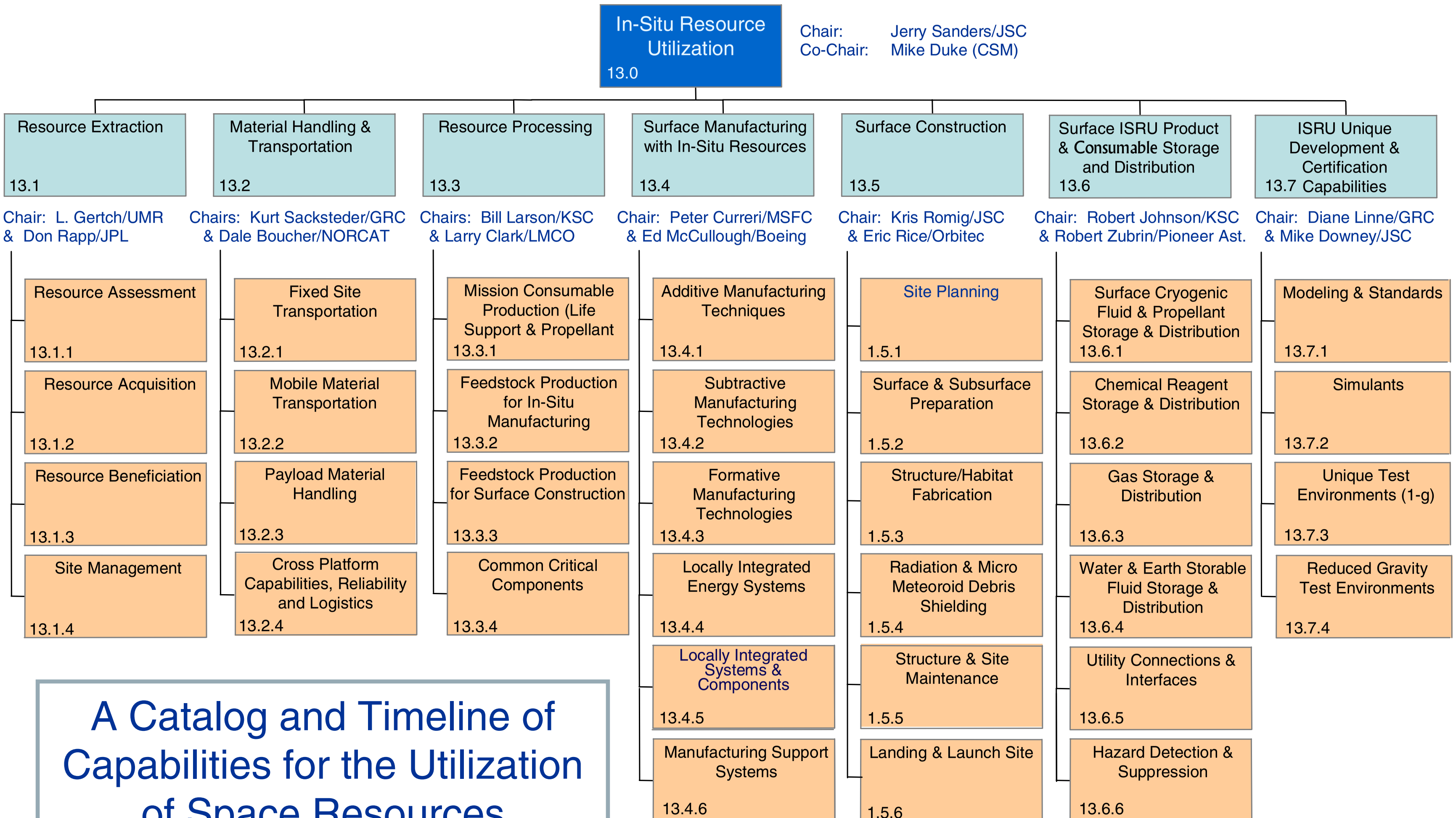
NASA ISRU Capability “Roadmap” Study, 2005



A Catalog and Timeline of Capabilities for the Utilization of Space Resources

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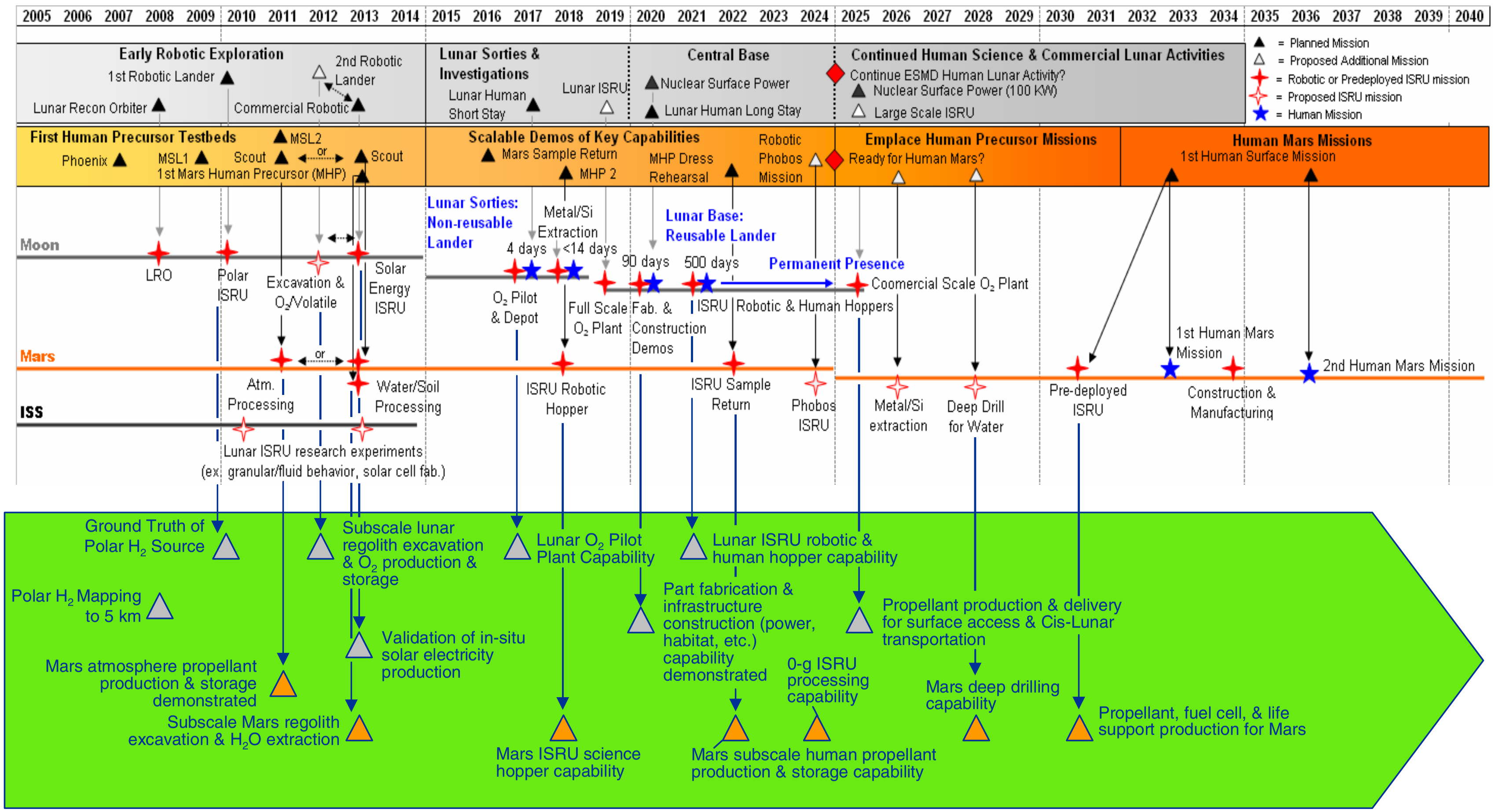
Timeline for ISRU Capability Implementation



In-Situ Resource Utilization must earn acceptance for mission critical roles in crewed missions through convincing demonstrations early in the Exploration timeline

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Lunar ISRU Implementation Approach

Lunar Mission Assumptions with ISRU (Lunar Exploration Analysis Group-LEAG)

- Robotic precursors identify resources and validate critical processes
- Early human missions (4 to 14 days) gain system & operational experience until a candidate long-term site is selected
  - Pre-deployed ISRU/mission assets before human missions
- Develop infrastructure at one base for Mars mission ‘dress rehearsals’ (90 day & 500 day) and sustained human presence in space
  - Traverse or hop to other locations for short term science mission objectives

Initial Capabilities

- Surface regolith excavation and manipulation
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O)
- Oxygen (O_2) production from regolith processing
- Production/regeneration of fuel cell reagents
- Cryogenic storage & transfer

Mid-Term ISRU Capabilities

- In-situ fabrication and repair
- Space Power
- Thermal energy storage & use

Long-Term Lunar Capabilities

- In-situ manufacturing of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- Life Support System – bio support (soil, fertilizers, etc.)
- Helium-3 isotope (^3He) mining

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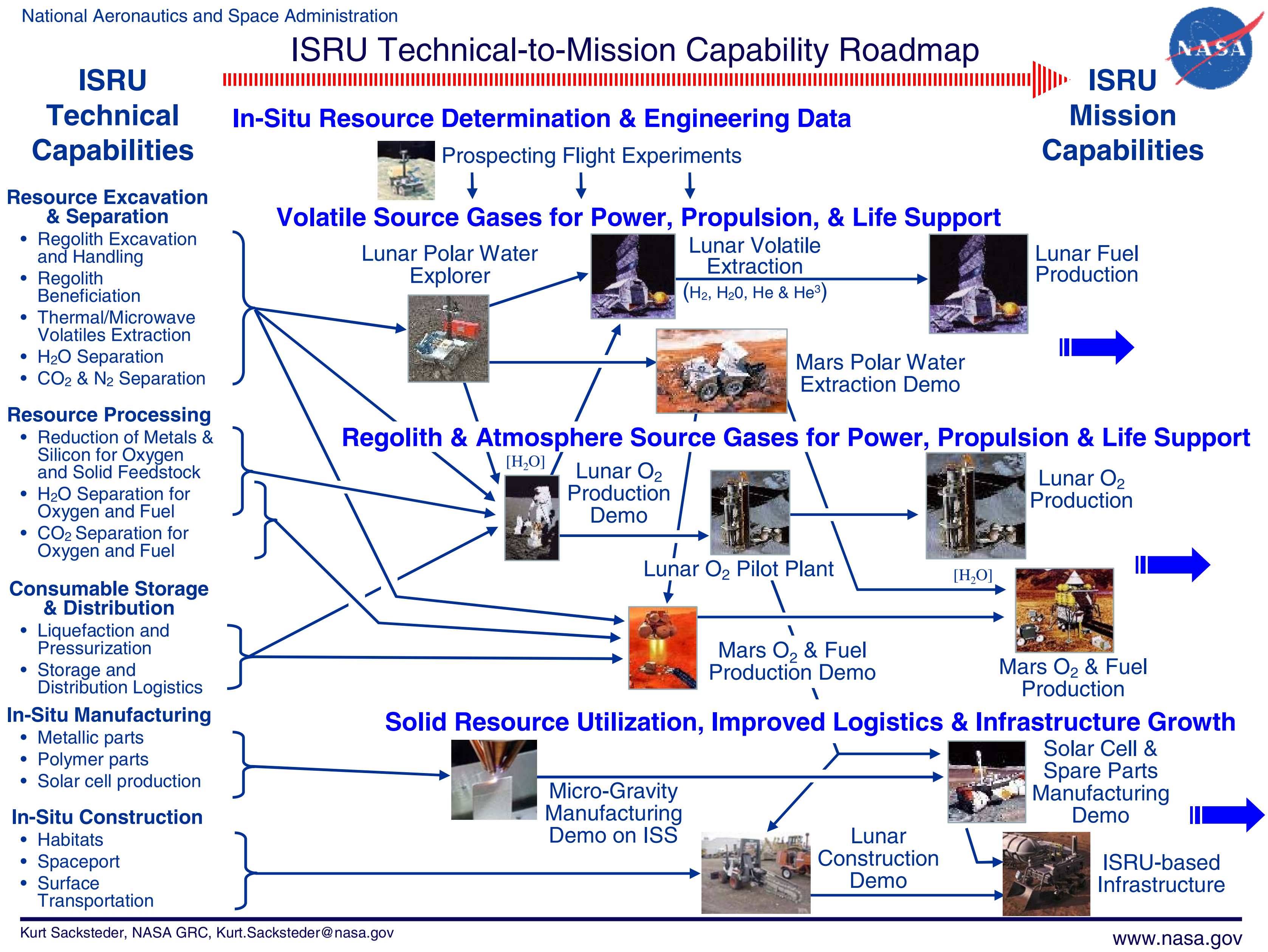
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ISRU Technical-to-Mission Capability Roadmap
ISRU Technical Capabilities
ISRU Mission Capabilities
Resource Excavation & Separation
• Regolith Excavation and Handling
• Regolith Beneficiation
• Thermal/Microwave Volatiles Extraction
• H_2O Separation
• CO_2 & N_2 Separation
Resource Processing
• Reduction of Metals & Silicon for Oxygen and Solid Feedstock
• H_2O Separation for Oxygen and Fuel
• CO_2 Separation for Oxygen and Fuel
Consumable Storage & Distribution
• Liquefaction and Pressurization
• Storage and Distribution Logistics
In-Situ Manufacturing
• Metallic parts
• Polymer parts
• Solar cell production
In-Situ Construction
• Habitats
• Spaceport
• Surface Transportation
In-Situ Resource Determination & Engineering Data
Prospecting Flight Experiments
Volatile Source Gases for Power, Propulsion, & Life Support
Lunar Polar Water Explorer
Lunar Volatile Extraction
(H_2, H_20, He & He^3)
Lunar Fuel Production
Mars Polar Water Extraction Demo
Regolith & Atmosphere Source Gases for Power, Propulsion & Life Support
[H_2O]
Lunar O_2 Production Demo
Lunar O_2 Pilot Plant
Lunar O_2 Production
[H_2O]
Mars O_2 & Fuel Production Demo
Mars O_2 & Fuel Production
Solid Resource Utilization, Improved Logistics & Infrastructure Growth
Micro-Gravity Manufacturing Demo on ISS
Solar Cell & Spare Parts Manufacturing Demo
Lunar Construction Demo
ISRU-based Infrastructure
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ISRU Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

Ilmenite - 15%

$FeO \bullet TiO_2$	98.5%

Pyroxene - 50%

$CaO \bullet SiO_2$	36.7%
$MgO \bullet SiO_2$	29.2%
$FeO \bullet SiO_2$	17.6%
$Al_2O_3 \bullet SiO_2$	9.6%
$TiO_2 \bullet SiO_2$	6.9%

Olivine - 15%

$2MgO \bullet SiO_2$	56.6%
$2FeO \bullet SiO_2$	42.7%

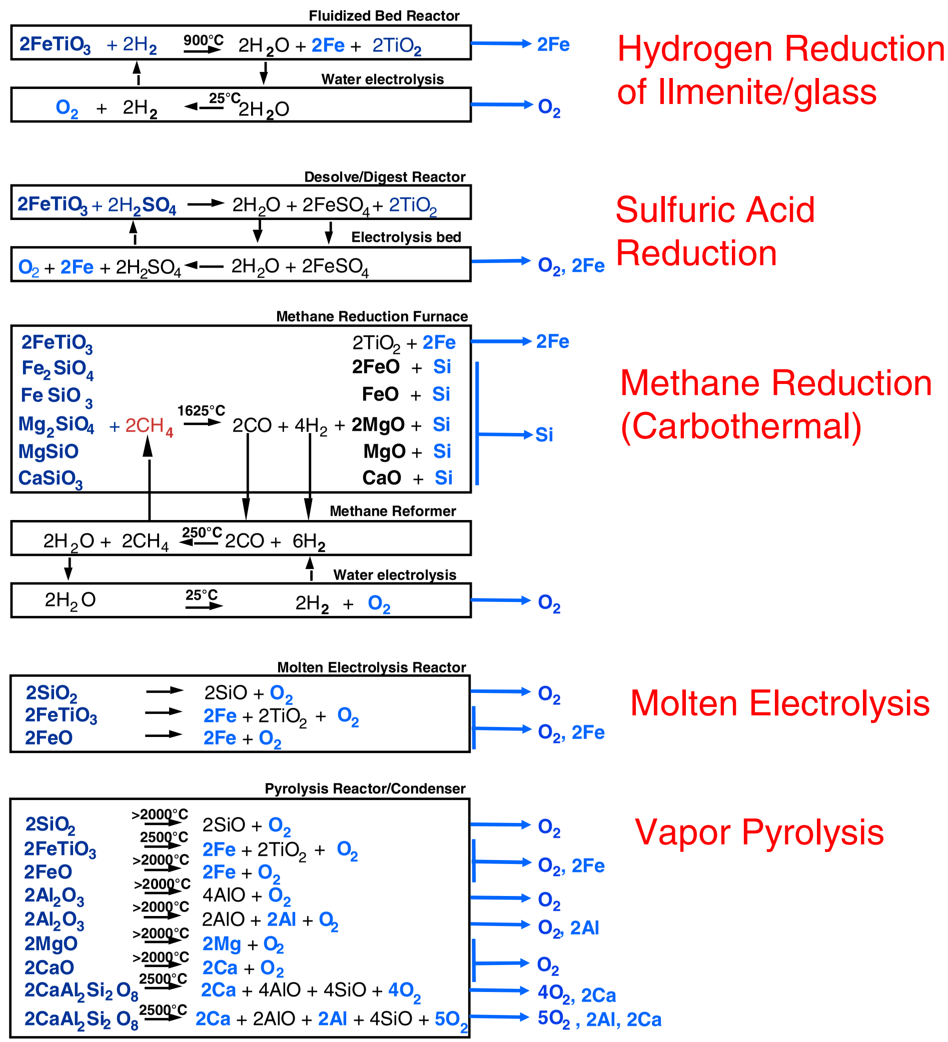
Anorthite - 20%

$CaO \bullet Al_2O_3 \bullet SiO_2$	97.7%

VOLATILES (Solar Wind & Polar Ice/H_2)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_2O)/H_2	1 - 10%

→ Thermal Volatile Extraction



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Challenging Seals Requirements for ISRU

The Moon is a Harsh Environment

- Temperatures from 40K (-230C) to 450K (150C)
- High Vacuum, 10^{-10} mm Hg
- Dust: abrasive, static cling, etc.
- Partial gravity

Initial ISRU Capabilities

- Surface regolith excavation and manipulation – mechanism bearings and regolith abrasion
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O) – encapsulate regolith during excavation and heating
- Oxygen (O_2) production from regolith processing – high temperature reactors and reagent recovery systems
- Production/regeneration of fuel cell reagents – fuel transfer operations
- Cryogenic storage & transfer – valves and other plumbing issues

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