In-Situ Resource Utilization (ISRU) Capability Roadmap Progress Review

Gerald B. Sanders - NASA Chair
Dr. Michael Duke - External Chair
April 12, 2005
Presentation Agenda

8:00 – 8:30  Introduction by APIO  R. Mueller
8:30 – 9:15  13.0 Level 1 Overview for ISRU  G. Sanders
9:15 – 9:45  - ISRU Architecture for ESMD  G. Sanders
9:45 – 10:30 13.1 Resource Extraction  L. Gertch
10:30 – 11:15 13.2 Resource Handling & Transportation  K. Sacksteder
11:15 – 12:00 13.3 Resource Processing  W. Larson
12:00 – 1:00  Lunch
1:00 – 1:45  13.4 Surface Manufacturing w/ In-Situ Resources  P. Currieri
1:45 – 2:30  13.5 Surface Construction  K. Romig
2:30 – 3:15  13.6 Surface Product/Consumable Storage & Distribution  R. Johnson
3:15 – 3:45  13.7 Unique ISRU Dev. & Cert. Capabilities  D. Linne
3:45 – 4:10  ISRU Commercialization  B. Blair
4:10 – 4:30  ISRU Presentation Summary  G. Sanders
4:30 – 5:30  Wrap up by NRC panel: synthesis of comments and recommendations
5:30  Adjourn
Presentation Material

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization (ISRU) Capability Roadmap: Level 1
  - Capability Roadmap Team
  - Benefits of the ISRU
  - Capability Description and Capability Breakdown Structure
  - Interdependency with other Capability Teams & Internal Links
  - Roadmap Process and Approach
  - Top-Level Metrics & Assumptions
  - Roadmap
  - Development Strategy

- ISRU ‘Emphasized’ Architecture Overview
  - ISRU-Enhanced Architectures Aimed At NASA Human Exploration Initiative
  - ISRU-Commercial Architecture Aimed At All Government & Commercial Applications

- ISRU Capability Elements: Level 2 and below
  - Capability Description, CBS, Attributes, & Benefits
  - Capability Requirements and Assumptions
  - Interdependency with other Capability Teams & Internal Links
  - Roadmap for Capability
  - Capability Current State-of-the-Art
  - Maturity Level - Capabilities
  - Maturity Level – Technologies
  - Gaps, Risks, & Strategy
  - Metrics
  - Level 3 charts as backup

- ISRU Capability Roadmap Wrap-up
  - ISRU Capability Challenges
  - ISRU Capability State of the Art
  - Gaps, & Risks Roll-up
  - ISRU Capability Roadmap Team Recommendations
  - Summary and Forward Work
Capability Roadmap Team – Level 1

Co-Chairs

NASA: Gerald B Sanders, NASA/JSC
External: Dr. Michael Duke, Colorado School of Mines

Government: NASA

- Diane Linne, GRC
- Kurt Sacksteder, GRC
- Stu Nozette, HQ
- Don Rapp, JPL
- Mike Downey, JSC
- David McKay, JSC
- Kris Romig, JSC
- Robert Johnson, KSC
- William Larson, KSC
- Peter Curreri, MSFC

Other/Critical Volunteers

- Dale Boucher, NORCAT
- Trygve “Spike” Magelssen, Futron
- Alex Ignatiev, Univ. of Houston
- Darryl Calkins/Army Cold Regions Research & Eng. Lab
- Klaus P. Heiss, High Frontier
- Tom Simon, JSC
- Ron Schlagheck, Laurent Sibille, Ray French, Julie Ray, & Mark Nall, MSFC

Industry

- Ed McCullough, Boeing
- Eric Rice, Orbitec
- Larry Clark, Lockheed Martin
- Robert Zubrin, Pioneer Astronautics

Academia

- Brad Blair, Colorado School of Mines
- Leslie Gertsch, Univ. of Missouri/Rolla

Further list of volunteers for each ISRU Element team

Broad ISRU industry & academic community (Space Resources Roundtable & STAIF Conferences)

Coordinators

Directorate: John Mankins, ESMD
APIO/JPL: Rob Mueller, Affiliation
What are Space Resources?

- **Traditional ‘Resources’:**
  - Water, atmospheric constituents, volatiles, solar wind volatiles, minerals, metals, etc.

- **Energy**
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Cold sink for cryo fluid storage & scientific instruments

- **Environment**
  - Vacuum/Dryness
  - Micro/Reduced Gravity
  - High Thermal Gradients

- **Location**
  - Stable Locations/’Real Estate’:
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

**The purpose of In-Situ Resource Utilization (ISRU) is to harness & utilize these resources to create products & services which enable and significantly reduce the mass, cost, & risk of near and long-term space exploration**
Uses of Space Resources for Robotic & Human 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.)
Benefits of ISRU: Critical for Affordable, Flexible, & Sustainable Exploration

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

Risk Reduction & Flexibility
- Number of launches & mission operations reduced
- Reduces dependence on Earth
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding

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

Space Resource Utilization
- Develops material handling and processing technologies
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

Expands Human Presence
- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

Enables Space Commercialization

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To Meet NASA’s Mission and to meet the challenge “to explore the universe and search for life” robotic and human exploration must be **Sustainable, Affordable, Flexible, Beneficial, and Safe**

<table>
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<tr>
<th>Strategic Challenges</th>
<th>How ISRU Meets Challenge</th>
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<tbody>
<tr>
<td>Margins &amp; Redundancy</td>
<td><strong>Use of common technologies/hardware and mission consumables enables swapping/cross use</strong>&lt;br&gt;See ASARA</td>
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<tr>
<td>Reusability</td>
<td>Production of mission consumables (propellants, fuel cell reagents, science gases, etc.) enables reuse of typical single use assets</td>
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<tr>
<td>Modularity</td>
<td>ISRU utilizes common technologies/hardware with life support, fuel cell power, and propulsion systems</td>
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<tr>
<td>As Safe As Reasonably Achievable (ASARA)</td>
<td><strong>Use of functional/dissimilar redundancy for mission critical systems (such as life support) increases mission safety</strong>&lt;br&gt;<strong>ISRU can eliminate aborts which may occur without capabilities: life support, power, spare parts, etc.</strong>&lt;br&gt;<strong>ISRU can reduce number of launches and mission operations increasing mission success probability</strong>&lt;br&gt;<strong>Use of in-situ materials for radiation shield enable lower levels of radiation exposure compared to Earth provided shielding</strong></td>
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<td>Robotic Networks</td>
<td>ISRU incorporates robotic networks to enable ISRU capabilities before human occupation</td>
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<tr>
<td>Affordable Logistics Pre-Positioning</td>
<td>ISRU enables large mass leveraging of pre-positioned hardware into usable mission products and consumables (space parts, propellants, life support gases, etc.)</td>
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<tr>
<td>Energy Rich Systems &amp; Missions</td>
<td>Regeneration of fuel cell reagents and common mission consumables and hardware enables power-rich surface elements, such as EVA suits, robotic assistants, and rovers, without the cost/overhead associated with multiple nuclear assets (RTGs)</td>
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<tr>
<td>Access to Surface Targets</td>
<td>Production and regeneration of propellants and fuel cell reagents enables transport rovers and robotic and human surface hoppers at a fraction of the cost compared to dedicated missions launched from Earth</td>
</tr>
<tr>
<td>Space Resource Utilization</td>
<td>All of above</td>
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Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

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In-Situ Resource Utilization Elements

**In-Situ Resource Extraction & Transport**

Involves assessment of resources, and extraction, excavation, and delivery of resources in low and micro-g environments, including the simple extraction and separation of resources from bulk resources.

**Surface Manufacturing w/ Space Resources**

Involves production of replacement parts, complex products, machines, and integrated systems from one or more processed resources.

**Resource Processing**

Involves multi-step thermal, chemical, and electrical processing of extracted resources into products with immediate use or as feedstock.

**Surface ISRU Product and Consumable Storage & Distribution**

Involves the ability to efficiently store and transfer the resource processing reagents and products, including resource recovery and system health approaches.
In-Situ Resource Utilization (ISRU) Capability Breakdown Structure

**Resource Extraction**
13.1

**Material Handling & Transportation**
13.2

**Resource Processing**
13.3

**Surface Manufacturing with In-Situ Resources**
13.4

**Surface Construction**
13.5

**Surface ISRU Product & Consumable Storage and Distribution**
13.6

**ISRU Unique Development & Certification Capabilities**
13.7

**Resource Assessment**
13.1.1

**Resource Acquisition**
13.1.2

**Resource Beneficrixion**
13.1.3

**Site Management**
13.1.4

**Mission Consumable Production (Life Support & Propellant)**
13.3.1

**Feedstock Production for In-Situ Manufacturing**
13.3.2

**Feedstock Production for Surface Construction**
13.3.3

**Additive Manufacturing Techniques**
13.4.1

**Subtractive Manufacturing Technologies**
13.4.2

**Formative Manufacturing Technologies**
13.4.3

**Locally Integrated Energy Systems**
13.4.4

**Locally Integrated Systems & Components**
13.4.5

**Manufacturing Support Systems**
13.4.6

**Site Planning**
1.5.1

**Surface & Subsurface Preparation**
1.5.2

**Structure/Habitat Fabrication**
1.5.3

**Radiation & Micro Meteoroid Debris Shielding**
1.5.4

**Structure & Site Maintenance**
1.5.5

**Landing & Launch Site**
1.5.6

**Surface Cryogenic Fluid & Propellant Storage & Distribution**
13.6.1

**Chemical Reagent Storage & Distribution**
13.6.2

**Gas Storage & Distribution**
13.6.3

**Water & Earth Storable Fluid Storage & Distribution**
13.6.4

**Utility Connections & Interfaces**
13.6.5

**Hazard Detection & Suppression**
13.6.6

**Fixed Site Transportation**
13.2.1

**Mobile Material Transportation**
13.2.2

**Payload Material Handling**
13.2.3

**Cross Platform Capabilities, Reliability and Logistics**
13.2.4

**Common Critical Components**
13.3.4

**Locally Integrated Energy Systems**
13.4.4

**Structure & Site Maintenance**
1.5.5

**Landing & Launch Site**
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**Hazard Detection & Suppression**
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**Modeling & Standards**
13.7.1

**Simulants**
13.7.2

**Unique Test Environments (1-g)**
13.7.3

**Reduced Gravity Test Environments**
13.7.4

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Chair: L. Gertch/UMR & Don Rapp/JPL
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Chair: Robert Johnson/KSC & Robert Zubrin/Pioneer Ast.
Chair: Diane Linne/GRC & Mike Downey/JSC
Initial surface power needs will be provided by *High Energy Power & Propulsion*
- Stationary Nuclear and/or solar power; mobile fuel cells/batteries for surface mobility
- *ISRU* will provide fuel cell consumable storage & distribution & may provide infrastructure power growth (generation and power management & distribution)

*ISRU* will provide surface propellant storage and distribution for ascent & hopper propulsion, to *In-Space Transportation*

*ISRU* will provide backup life support consumable production, storage, and distribution for *Human Health & Support Systems*

Space propellant depots will be provided by *In-Space Transportation*
- *ISRU* may provide propellants for delivery to depots

Surface Mobility assets for ISRU excavation and transport will be provided by the *Human Exploration Systems & Mobility* capability
- *ISRU* will provide unique excavation and material handling & transportation units

*Scientific Instruments & Sensors* should be provide instruments to locate and quantify potential resources
- *ISRU* may be responsible for sensors for in-situ evaluation of resource characteristics and performance

*Autonomous Systems & Robotics* will provide autonomous control & failure detection, isolation, & recovery hardware and software
- *ISRU* will provide unique excavation, transport, & processing software

*ISRU* will provide any construction requiring use or manipulation of local materials
- Habitat construction through assembly of pre-built units delivered from Earth would be provided by *Human Health & Support Systems*

*ISRU* will provide manufacturing processes that use local materials or in-situ products
Example ISRU to Other Capabilities

**ISRU Products To Other Capabilities**

- $\text{H}_2$ & $^3\text{He}$ for NTR & fusion; Ar for electric
- Solar array and collector manufacturing & assembly
- Rectenna fabrication for orbital power beaming
- Thermal storage material production & fabrication
- Radiation shields for nuclear reactors

**Capability Products To ISRU**

- Solar & nuclear power to support power-intensive ISRU activities

**Symbol Key**

- Color Denotes Criticality
- Arrow Point Denotes Direction

*Criticality From Resource To Extraction High Energy*

*Criticality From High Energy To Resource Extraction*

*Criticality From Material Handling & Transportation To Resource Extraction*

*Criticality From Resource Extraction To Material Handling & Transportation*
### ISRU Products To Other Capabilities

- H₂ & ³He for NTR & fusion;  Ar for electric
- Solar array and collector manufacturing & assembly
- Rectenna fabrication for orbital power beaming
- Thermal storage material production & fabrication
- Radiation shields for nuclear reactors
- Power cable deployment; in-situ provided power management & distribution

- Propellant production and pressurant/purge gases for lander reuse and in-space depots
- Aeroshells from Regolith

- Shaping crater for collector
- In-situ construction and fabrication; foundation design & preparation
- Gases for inflatable structures
- Raw materials for space based observatory manufacture

- Raw materials for infrastructure

- Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions)
- Propellant production for surface hoppers or large sample return missions

- Landing pads/plume debris shielding
- Propellant production/storage/transfer for lander reuse

### Capability Products To ISRU

- Initial solar & nuclear power to support power-intensive ISRU activities
- Mobile/high-density power sources.

- ISRU-compatible propulsion
- Delivery of ISRU products to sites of exploration and in-space depots

- Mobile equipment navigation.
- Fast communication among systems components.

- Resource location & characterization information
- Surface mobility system design & experience
- Pre-positioning & activation of ISRU assets

- Precision landing
- Delivery of ISRU capabilities to sites of exploration
### ISRU Products To Other Capabilities

- Habitat/shelter fabrication
- Gases for inflation & buffer gases
- Life support consumable production for backup
- Radiation & micro-meteoroid debris shields from in-situ material
- Soil & bio-feedstock for plant growth
- Materials for in-situ manufacturing

- Gases for science equipment
- Propellants & fuel cell reactants for surface vehicles and aero-bots
- \( \text{O}_2 \) production for EVA
- Soil stabilization/dust control
- Roadway infrastructure
- Engineering properties of regolith

- Fuel cell reactants for surface vehicles and aero-bots
- New & replacement parts for robotic systems

- Gases and explosives for science equipment
- Increased sample and measurement density for science studies.

### Capability Products To ISRU

- Carbon-based waste products as resource for ISRU
- Common hardware for possible modularity with ISRU systems

- Crew/robotics/rovers to perform ISRU surface activities

- Robots/rovers to perform ISRU surface activities
- Software & FDIR logic for autonomous operation

- Resource location & characterization information
- Self Calibrating or Extended Calibration Life Sensors

- Resource formation models.
- Mining and reclamation method evaluation.
- Resource delivery and distribution models.
- Granular material performance models.

- Nanotube catalysts for Microchemical Reactors
## ISRU Element Interdependency With Other Capabilities

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**2. High energy power and propulsion**

**3. In-space transportation**

**4. Advanced telescopes and observatories**

**5. Communication and navigation**

**6. Robotic access to planetary surfaces**

**7. Human planetary landing systems**

**8. Human health and support systems**

**9. Human exploration systems and mobility**

**10. Autonomous systems and robotics**

**11. Transformational spaceport/range technologies**

**12. Scientific instruments and sensors**

**13. Advanced modeling, simulation, analysis**

**14. Systems engineering cost/risk analysis**

**15. Nanotechnology**

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### ISRU Element Interdependency Summary

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- **Hi Criticality**: High interdependency between elements.
- **Med Criticality**: Medium interdependency between elements.
- **Lo Criticality**: Low interdependency between elements.
- **No Criticality**: No interdependency between elements.
ISRU Roadmap Process and Approach

- Establish work structure that will be utilized in Phase I and II
  - Form separate teams for each main ISRU CBS Element (6) with co-leads from different NASA centers and industry/academia
    - Volunteers from NASA, industry, & academia supported each Element team
  - Form separate team to examine Design Reference Architectures & Missions (DRAs/DRMs) and work with ISRU CBS teams to determine applicability and uses, and propose/work mission studies to define benefits/impacts
  - Establish ties to leads in other linked-dependant Capability Roadmaps:

- CBS Element Co-Leads will identify/lead external volunteers to develop roadmap products for their Element
- Chairs & Element Leads will integrate roadmap elements
- Method of performing work:
  - Weekly telecoms of Chairs with CBS element leads (Steering Committee)
  - Weekly telecoms of CBS element activities
  - Outreach Workshops (Space Resources Roundtable 11/04, APIO Workshop 11/04, & STAIF 2/05)
  - Face-to-face team meetings (3)
### Top Level ISRU Metrics

#### Concept Evaluation Criteria
- Complexity/Risk
  - ISRU process/service
  - Compared to “bring from Earth” approach
- Ability to Enable Mission Goals/Objectives
  - Sustained human presence & long-term self-sufficiency
  - Ability of hardware/technology to be used in multiple applications & destinations
- Growth potential

#### Process Evaluation Criteria
- ‘Launch mass saved’ or ‘Launch mass avoided’ (immediate & long-term)
  - Ability to provide immediate/early impact on mission
  - Rate of return on investment by Gov or Commercial Enterprise
- Reliability/Mean Time Between Repairs (MTBR)
- Equipment/system working life
- Mass of product/service vs Mass of ISRU “system”
- Production rate or mass of product vs Unit power consumed
- Mass throughput (volumetric or mass flowrate)
- Percent of Earth consumable required (immediate & long-term)
- Degree of system/process autonomy
Design Framework/Reference Mission Requirements & Assumptions or ISRU CRM

Team 13: In-Situ Resource Utilization

- Information & metrics from mission studies that did include ISRU (Mars ’98) were utilized to the maximum extent possible
  - Mission and transportation asset information from other studies were also used to the maximum extent possible

- Because almost all missions studies to date have not include ISRU from the start, notional ISRU architectures were created to determine impacts & relative benefits
  - **ISRU-Emphasized Architectures** Aimed at NASA Human Exploration Initiative
    - ISRU-Enhanced Architecture
    - Derivation 1: Direct Return – ISRU Architecture
    - Derivation 2: E-M L1 propellant for Moon/Mars
  - **ISRU Commercial Architecture** Aimed at All Government (NASA Human & Science, DOD, NOAA) & Space Commercial Applications

- ISRU Incorporation & Evolution Philosophy
  - Characterize resources and validate ISRU concepts in Spiral 1
    - **Perform ISRU pilot operations in Spiral 2 to enhance missions and support full use at start of Spiral 3**
  - Develop lunar ISRU as a precursor to Mars missions as well as enable sustained human lunar operations

**Note:** The cost for implementing demonstrations & missions in the defined ISRU Architectures has not yet been performed. It should also be noted that a Driving Principle of ISRU incorporation is to reduce costs both in the near and far-term. Therefore, reprioritization and rescheduling may need to be necessary.
ISRU Usage & Incorporation Assumptions

- **Spiral 2 & beyond**
  - Surface mobility systems will utilize In-situ produced fuel cells reagents
  - ISRU systems will generally be pre-deployed by robotic missions and will operate autonomously for extended periods of time
  - Power systems will be available (either Earth emplaced or ISRU enhanced) to supply the needs of ISRU systems even in the permanently shadowed craters of the moon.

- **Spiral 3 & beyond:**
  - Reusable landers will land “empty” and be refueled on the surface
  - Long-term missions will require the production of manufacturing feedstocks
  - Permanent presence on other planetary bodies will require the in-situ production of construction materials

- **Architecture assumptions**
  - For conservatism, Lunar ISRU assumed oxygen production thru hydrogen reduction of regolith
  - Production of propellants for surface to orbit ascent as minimum
    - Human Lunar ascent vehicles require 20-30 MT of propellant
    - Human Mars ascents vehicles require 30-50 MT of propellant
  - Significant power (nuclear) required at start of vehicle propellant production capabilities:
    - \(+300\) KWe for Moon in \(+2018\)
    - \(+30\) KWe for Mars in \(+2028\)
Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2005 to 16)

Key Assumptions:
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone
- ISS
- Moon
- Mars

**Capability Roadmap 13: ISRU**

13.1 Resource Extraction
- Polar H₂ Mapping to 5 km
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated
- 0-g manufacturing & repair demonstrated

13.2 Material Transportation
- Polar shadow regolith (<1m)

13.3 Resource Processing
- Polar shadow regolith (<0.25 kg/op)

13.4 Surface Manufacturing
- ISS Repair Unit < 95% Reliability
- 5 Kg PV quality Si/metal from lunar regolith
- Solar cell on glass > 5% Efficiency

13.5 Surface Construction
- Autonomous site planning & clearing
- O₂ liquefaction & storage (2-4 kg)

13.6 Surface Storage & Distribution
- Polar shadow testing (40 K)
- Lunar env. & regolith (1m depth)
- Combined Mars env., regolith, & water simulation

13.7 ISRU Unique
- Mars atm. & dust environment, simulation
- O₂ Transfer
- O₂ liquefaction & storage (5 kg/hr; x kg)

Mars Pilot & Depot
- Lunar O₂ Pilot Plant Capability (30-60 KWe)
- ISRU science hopper capability (0.5-2 KWe)

Subscale lunar regolith excavation & H₂O extraction
- Validation of in-situ solar electricity production
- Validation of silicon/metal extraction from lunar regolith

Mare/HL (50 kg/hr)
Mars regolith (<3m)
Mars O₂ from Mare/HL (1200 kg)
Mars O₂ from Atm. (500-1000 kg)
Mars O₂ to fuel from Atm. (2-4 kg)
Mars Atm.

Subscale Mars regolith excavation & H₂O extraction
- Separate excavation & transport units
- Mars regolith (integrated)

Mars O₂ from Mare/HL (2-4 kg/hr)
Mars O₂ from Atm. (x kg/hr)
Mars O₂ from Mare/HL (50 kg/hr)
Mars O₂ from Atm.

ISS
- LRO
- Resource Underpinnings
- Solar Energy
- Water/Soil Processing
- Solar cell on glass
- > 5% Efficiency
- 5 Kg PV quality Si/metal from lunar regolith
- Autonomous site planning & clearing
- O₂ liquefaction & storage (2-4 kg)

Moon
- Lunar O₂ Pilot Plant Capability (30-60 KWe)
- ISRU science hopper capability (0.5-2 KWe)
- Moon O₂ from Atm. (y kg/hr)
- Moon O₂ from Atm. (z kg/hr)
- Moon O₂ to fuel Liq/Storage.
- (500-1000 kg)

2005 2010 2015
Not Everything Can Be Funded Immediately

Need *Early, Achievable, & Visible* milestones & successes
  – Must ensure constant delivery of products; with incremental growth in both number of products & quantity of products
  – Early missions must require minimum infrastructure and provide the biggest mass/cost leverage
  – Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capability

Need to take Evolutionary approach In development & missions
  – Early hardware needs to be achievable, not optimized
  – Early hardware needs to be scalable to future missions
  – Each design/demonstration activity needs to build on lessons learned from previous work and show clear benefit metrics
  – Research activities and technology development must be continuously performed and focused to enable sustained momentum and growth
  – Capabilities need to be able to grow with growth in:
    • Resource & process understanding
    • Human surface activities

No single process or technology is best
  – Develop two or more approaches if possible to ensure success
In-Situ Resource Utilization (ISRU)

Emphasized Architecture Overview

ISRU Capability Roadmap Team

NASA Chair: Jerry B. Sanders, NASA/JSC, gerald.b.sanders@nasa.gov
External Chair: Dr. Michael Duke, Colorado School of Mines, mduke@mines.edu
Architecture Concepts

- **Current Lunar Mission Architecture Options**
  - Option A: Lunar Evolution
  - Option B: Early Outpost
  - Option C: Early Lunar Resources
  - Option D: Expedited Moon-to-Mars

- **ISRU-Emphasized Architectures Aimed At NASA Human Exploration Initiative**
  - ISRU-Enhanced Architecture
  - Derivation 1: Direct Return – ISRU Architecture
  - Derivation 2: E-M L1 propellant for Moon/Mars

- **ISRU-Commercial Architecture Aimed At All Government (NASA Human & Science, DOD, NOAA) & Commercial Applications**
Current Lunar Mission Architecture Options

- **Option A: Lunar Evolution**
  - Robotic missions start prior to 2010 and continue throughout lunar program
  - Human ‘sortie’ missions begin in 2015 to 2020 timeframe
  - Expanded lunar science and Mars short-stay mission demonstrated in 2020 to 2025 timeframe
  - Decision in 2025-2030: 1) continue as ‘outpost’, 2) develop ‘base’ for long-term stay tests, 3) develop expanded ‘McMurdo’ type base, 4) decrease lunar activities, & 5) abandon human lunar activities

- **Option B: Early Outpost**
  - Minimize ‘sortie’ missions and focus on early Mars short-stay and expanded lunar science in 2015 to 2020
  - Same Decision as Option A: Lunar Evolution but now in 2020 to 2025 timeframe

**Option C: Early Lunar Resources** (leverage ISRU to maximum extent possible)
  - Same start as Option B: Early Outpost which continues into 2020-2025 period
  - Also Decision made in 2020-2025 timeframe

- **Option D: Expedited Moon-to-Mars**
  - Human ‘sortie’ missions begin in 2015-2020 timeframe geared towards Mars operation development & testing
  - This option does not conduct missions for purpose of demonstrating technologies
  - Human Lunar activities end in 2020 to 2025 time period
ISRU-Enhanced Architectures Aimed At NASA Human Exploration
Space Resource Utilization Dependencies

Architecture dependant:

- Long stay vs short stay (mission consumable mass increases with stay time)
- Pre-deploy vs all in one mission (pre-deploy allows longer production times but requires precision landing)
- Multiple mission to same destination vs single missions (multiple missions enables gradual infrastructure and production rate build up)
- High orbit vs low orbit rendezvous (increase in Delta-V increases benefit of in-situ produced propellant)
- Reuse vs single mission (reuse allows for single stage vs two stage landers and lower cost propellant depots at E-M L1)

Customer dependant:

- ISRU use must be designed into subsystems that utilize the products (propellants, radiation shielding, energy storage, surface equipment, spare parts, etc.) from the start to maximize benefits
Objectives of Lunar ISRU Development & Use

- Identify and characterize resources on Moon, especially polar region
- Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions as early as possible to utilize at start of Spiral 3
  - Excavation and material handling & transport
  - Oxygen production and volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems
  - Cryogenic fluid storage & transfer
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables (*propellants, life support, power, etc.*)
  - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
  - ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals
- Develop and evolve lunar ISRU capabilities that *enable* exploration capabilities
  - ex. Long-range surface mobility, global science access, power-rich distributed systems, enhanced radiation shielding, etc.
- Develop and evolve lunar ISRU capabilities to support sustained, economical human space transportation and presence on Moon
  - Lower Earth-to-Orbit launch needs
  - Enables reuse of transportation assets and single stage lander/ascent vehicles
    - Lower cost to government thru *government-commercial* space commercialization initiatives
Objectives of Mars ISRU Development & Use

- Utilize Earth-based, ISS, and Lunar ISRU development, testing, and experience to maximum extent possible

- Identify and characterize resources on Mars, especially water
  - Utilize information from past, current, and planned Science missions to provide critical environment, resource, and design data when possible

- Develop and evolve Mars ISRU capabilities that reduces cost, mass, and risk of human exploration and enable exploration capabilities as early as possible
  - ex. Surface mobility & hoppers, power-rich distributed systems, enhanced radiation shielding, manufacturing/construction, plant growth/food production, etc.

- Perform ISRU demonstrations in step-wise approach to increase confidence in environment/resource understanding and reduce mission application uncertainties
  Experiment development time, 26 month gaps in missions, trip times, and extended surface operations mean lessons learned from one mission can only influence missions 2 or 3 opportunities (4 or 6 years) later
  - Parallel investigations of atmospheric and regolith/water-based processing with convergence before human mission

- Enable human missions beyond Mars (gateway to asteroid belt?)
  - ISRU on Phobos/Deimos; Mars-Sun L1 depot; ....
  - Space exploration is “a journey, not a race”
ISRU-Emphasized Architecture Attributes

- No Earth launch vehicle assumption made
- Crew of 4 or 6 assumed up to permanent presence; TBD (12) at permanent presence
- Characterize resource, environment, & engineering unknowns as early as possible
  - Lunar polar and global resources; Mars water form and availability
  - Higher resolution of minerals/resources & surface topography
  - Critical material & engineering properties
- Utilize ISS for ISRU-related research
  - Manufacturing & repair
  - Gravity influences on fluid behavior, material handling, and processing
- Develop single robust primary lunar exploration site:
  - Initial checkout flights could be to different locations until final site selected
  - Use primary site before access other locations (e.g. McMurdo Station approach)
  - Evolve to ‘Short’ (<90 days) and ‘Long’ (500 days) Mars surface mission dress rehearsals
- Demonstrate ISRU in Spiral 2 and Utilize ISRU to support missions at start of Spiral 3
  - Robotically pre-deploy and operate assets/capabilities: enable large mass/capability leverage
  - Use modular approach to incrementally develop and expand/grow capabilities
  - Develop life support backup, power, & manufacturing/repair capabilities
  - Begin use of lunar derived propellants & reusing transportation elements
    - Lunar oxygen; fuel trades still required
    - Initially propellant for lunar ascent (to LLO, E-M L1, or direct Earth return)
    - Increase capability to deliver propellant to E-M L1 and potentially LEO
- Develop lunar infrastructure and operations to enable sustainable lunar operations in parallel with a Mars exploration program
ISRU-Emphasized Architecture Benefits

Spiral 1 Benefits
- Lunar resource characterization and mapping for future human missions
- Validation of critical ISRU processes in actual environment (i.e. Lunar oxygen production, hydrogen/water extraction, excavation, etc.)

Spiral 2 Benefits:
- Demonstrate critical ISRU systems as additional capability in Spiral 2 and enable use at start of Spiral 3
  - Extra oxygen for EVA & life support use (possibly extend mission duration)
  - Extra power for operations & science

Spiral 3 Benefits:
- Lower mission costs:
  - 300 MT/yr reduced life support logistics for crew (LUNOX study)
  - Reduced transportation costs
    - Reuse of assets ($10’s to $100’s M)
    - Reduction in payload to LEO; 1/3\textsuperscript{rd} compared to Non-ISRU architecture
- Increased mission capabilities
  - Increased landed payload capability with lunar propellant (x MT)
  - Smaller reusable lander; reduced penalty for increased redundancy/engine-out
  - Higher level of radiation protection for crew (ASARA)
  - Power rich exploration
  - Global surface access for increased science at significantly reduced cost compared to dedicated mission launched from Earth
  - Lunar ISRU-derived infrastructure (habitats, life support, power, etc.)
**Spiral 3 Benefits (Cont.):**
- Reduced mission risk (Spare manufacturing & repair, lower radiation, reduced number of mission events, etc.)
- ISRU operation and mission impact experience for Mars missions (Spiral 5)
  - Early Spiral 3/Shortened Spiral 2 timeline for reduced architecture costs
  - Increased science with extended surface mobility and global access

**Spiral 4 Benefits:**
- Examination of resource processing and use in micro-gravity
- Possible ISRU-Consumable depot on Phobos for Mars and beyond transportation

**Spiral 5 Benefits:**
- Lower mission mass (>20% reduction)
- Smaller landers/ascent vehicles; reduced penalty for increased redundancy/engine-out
- Global robotic sample acquisition access with ISRU hoppers
- Long duration surface stay consumables
- Reduced mission risk (more in-situ capabilities, lower radiation, reduced number of mission events, etc.)
Notional ISRU-Supported Mission Timeline
High Criticality-to-Mission Success/Cost Areas Strongly Affected by ISRU

- **Transportation** (In-space and surface)
- **Energy/Power** (Electric, thermal, and chemical)
- **Life Support** (Radiation protection, consumables, habitable volume, etc.)
- **Sustainability** (repair, manufacturing, construction, etc.)

**ISRU Demonstrations & Capabilities**

- Spiral 1 Resource Characterization and ISRU Validation Demonstrations
  - Characterization, excavation & transport of regolith
  - Oxygen (O₂) production from regolith (possibly propellant for Lunar sample return)
  - Polar Water/Hydrogen (H₂O/H₂) extraction
  - Volatile extraction (H₂, He³/He, N₂, etc.)
  - Metals extraction and separation from regolith
  - Energy generation and storage (solar & thermal)
  - Cryo fluid storage & transfer
  - Orbital ISRU Precursors: Global survey of resources & imaging in permanently shadowed craters

- Spiral 1 ISRU-Related Activities on the International Space Station (ISS)
  - Available hardware possible: Rapid Prototyping, Combustion Synthesis, Microgravity Glovebox
  - Manufacturing of parts: Demos and CEV & ISS parts fabrication (Polymer fabrication, direct metal/ceramic fabrication, mechanical properties comparison & analysis, etc.)
  - Repair & maintenance (Shuttle repair, lunar soil fusion, joining dissimilar materials, etc.)
  - Micro-g fluid/mat'l processing research (separators, reactors, fluidized beds, etc.)
  - Ultra-high vacuum for solar cell growth
- **Spiral 2 Lunar ISRU Demonstrations & Mission Enhancements**
  - Scalable excavation & transport of regolith
  - Site survey/preparation
  - Production, storage, & transfer of oxygen (O₂) and fuel cell reactants for EVA and surface mobility (use cryo tanks from lander or advanced cryo technology demonstration)
  - Long term operation and hardware evaluation
  - ISRU robotic hopper demonstration with 'there & back' capability; increased science, landing hazard avoidance, & human-related propulsion capabilities and synergism to Mars exploration

- **Spiral 2 Mars ISRU Demonstrations & Mission enhancements**
  - Site survey/preparation
  - Characterization, excavation & transport of regolith
  - Water (H₂O) extraction
  - Atmospheric processing for O₂ & fuel
  - Cryo fluid storage & transfer
  - ISRU robotic hopper & sample return mission
  - Human mission scale processing
Spiral 3 Lunar ISRU Mission Applications
- Single site preparation & construction (berms, radiation shielding, habitat deployment, etc.)
- \( \text{O}_2 \) production for EVA & life support backup and growth
- Propellant production & storage for ascent vehicles & hoppers
- Regeneration of fuel cell consumables
- Surface consumable storage depot & transfer capability
- Extraction & production of feedstock for construction & manufacturing
- Manufacturing capability for spare parts
- In-situ energy production capability expansion (solar & thermal)

Spiral 4 Small Body Demonstrations & Applications (Phobos, NEOs, etc.)
- Micro-gravity regolith excavation & transport
- Micro-gravity water extraction, separation, and processing
- Micro-gravity mineral/metal extraction

Spiral 5 Mars Demonstrations & Applications
- Site preparation & construction
- \( \text{O}_2 \) production for EVA & life support
- Propellant production & storage for ascent vehicles & hoppers
- Regeneration of fuel cell consumables
- Metals extraction and separation from regolith
- Manufacturing capability for spare parts
- Bio-soil processing for plant/food growth
Direct Return - ISRU Architecture

Architecture Attributes

- HLLV: 120 MT to LEO; 40 MT to LLO; 25 MT to lunar surface
- 25 MT payload can be Habitat, Cargo, or wet
  Earth Return Vehicle (ERV)
- ERV returns crew directly to Earth (no rendezvous)
- Large scale lunar oxygen \( (O_2) \) production
  - Water production if available
- Other attributes similar to Nominal ISRU Architecture

Benefits

- Number of Moon/Mars hardware elements developed is minimized
  - Common HLLV, Eliminates LSAM Development
- Number of mission-critical operations is minimized
  - Lower launches and no orbital rendezvous
- Cost & risk per person-day on Moon greatly reduced
  - Direct Return mission launch mass is lower than LOR once in situ-LOx is available.
  - Heavy cargo lander allows early delivery of substantial hab/lab to surface. Eliminates non-cost effective short-stay mission phase.
  - Safe haven on surface enhances crew safety.
  - Return launch window is always open.
- Accelerates transition to more productive Spiral 3

Additional Spiral 3 Benefits:

- Maximum ISRU leverage:
  - Global surface access with hoppers at significantly reduced cost (8 to 14 Lunar sites explored for delivery of one launch of fuel) [Zubrin study]
  - Reduction in Lunar launch requirements plus hardware commonality allows Mars program to proceed in parallel
- Accelerates transition to Mars, without abandoning Moon.
Architecture Attributes

- Assumes reusable/maintainable space transportation assets (3 or more missions)
  - Landers, trans-stages, crewed vehicles, surface & space depots, Earth aeroshells
- Staging at Low Earth Orbit (LEO) and Earth-Moon (E-M) Lagrange Point (L1)
- Lunar propellant transferred to E-M L1 and possibly to LEO
- Propellant used for
  - Lunar ascent/descent to/from E-M L1
  - Return to Earth from E-M L1
  - Earth LEO to E-M L1 (long range)
- Propellant delivery to E-M L1
  - If only Lunar Oxygen (LunOx) then transfer via chemical propulsion; long-term – tether or elevator
  - If lunar water is available, transfer as water/ice via chemical propulsion or electromagnetic launcher (best case)
- Depot at E-M L1 can provide low Delta-V to other destinations.
  - E-M L1 to Earth-Sun L1 = 850 m/s
  - E-M L1 to Mars = 1470 m/s
  - Note: Earth to LEO = 9200 m/s

Benefits

Additional Spiral 3 Benefits:

- Maximum ISRU leverage:
- Cost & risk per person-day on Moon further reduced
- Significantly reduced Earth launch rates and costs
  - Initial Mass in LEO is about 1/3 to 1/4 of that compared to non-ISRU mission [CSM study]
  - Reuse of space assets can further reduces initial mass to 1/8 of non-ISRU mission [CSM study]

Additional Spiral 5 Benefits

- Significantly reduced Earth launch rates and costs
Transfer Impulses in Near-Earth Space

- **LEO** (Low Earth Orbit)
- **GTO** (GEO Transfer Orbit)
- **GEO** (Geostationary Orbit)
- **EM L1** (Earth-Moon Libration Point L1)
- **SE L1** (Sun-Earth Libration Point L1)
- **SE L2** (Sun-Earth Libration Point L2)
- **LLO** (Low Lunar Orbit)

### Impulse Values

- **GTO** to **LEO**: 
  - \( \Delta V_{\text{High-T}} \approx 4,330 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 640 \text{ m/s} \)

- **LEO** to **GEO**: 
  - \( \Delta V_{\text{High-T}} \approx 3,770 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 6,800 \text{ m/s} \)

- **GEO** to **E-M L1**: 
  - \( \Delta V_{\text{High-T}} \approx 1,870 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 760 \text{ m/s} \)

- **E-M L1** to **S-E L1** and **S-E L2**: 
  - \( \Delta V_{\text{High-T}} \approx 2,520 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 5,200 \text{ m/s} \)

- **S-E L1** to **S-E L2**: 
  - \( \Delta V_{\text{High-T}} \approx 10 \text{ km/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 300-400 \text{ m/s} \)

- **E-M L1** to **LLO**: 
  - \( \Delta V_{\text{High-T}} \approx 3,000 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 5,800 \text{ m/s} \)

- **LLO** to **Earth**: 
  - \( \Delta V_{\text{High-T}} \approx 10 \text{ km/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 2,300 \text{ m/s} \)

- **Earth** to **Lunar Surface**: 
  - \( \Delta V_{\text{Low-T}} \approx 7,900 \text{ m/s} \)

- **Lunar Surface** to **E-M L1**: 
  - \( \Delta V_{\text{High-T}} \approx 1,380 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 400 \text{ m/s} \)

- **E-M L1** to **S-E L1**: 
  - \( \Delta V_{\text{High-T}} \approx 2,500 \text{ m/s} \)
  - \( \Delta V_{\text{Low-T}} \approx 7,320 \text{ m/s} \)
ISRU Sub-Element 13.1
Resource Extraction

Dr. Leslie Gertsch - External Chair
Don Rapp - NASA Chair
April 12, 2005
Co-Chairs

External: Leslie Gertsch, University of Missouri-Rolla
NASA: Don Rapp, JPL

Government: NASA
- Allen Wilkinson, GRC
- David McKay, JSC
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- Phil Metzger, KSC
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- Paul Corcoran, Karen Huber, & Sam Kherat, Caterpillar Equipment
- Jim Richard, Electric Vehicle Controllers Ltd.
- Jack Wilson & James Powderly, Honeybee Robotics
- Kevin Payne, Lockheed-Martin
- Dale Boucher, Northern Center for Advanced Technology
- Eric Rice, Orbitec

Academia
- Richard Gertsch, Michigan Technological University
- Brad Blair, Colorado School of Mines

Government: Other
- Darryl Calkins, Sally Shoop, Peter Smallidge, & Jerry Johnson; USACE Cold Regions Research & Engineering Lab

Other/Critical Volunteers
- Most of the above are volunteer contributors
- Broad ISRU industry & academic community (Space Resources Roundtable & STAIF Conferences)
Capability 13.1 Resource Extraction

Resource Extraction provides raw materials -- gas, liquid, and solid -- from the local environment by removing them, concentrating them, and preparing them for further processing, manufacturing, or direct use. It is the first step in “living off the land” in a sustainable manner.

It consists of four parts:

**Resource Assessment** determines what is available, where it is, what form it is in, and how it can best be extracted.

**Resource Acquisition** separates and removes the target raw material -- gas, liquid, and/or solid -- from its original location to Resource Beneficiation.

**Resource Beneficiation** converts the raw material into a form suitable for direct use, manufacturing, or further processing.

**Site Management** comprises supplemental capabilities needed for safe, effective operation.
Resource Extraction

Blue outline = major capability needed for 2005-2035
Dashed outline = commonality with other capability(ies)
Attributes and Benefits of Resource Extraction

- Provides **feedstock** for local manufacture of:
  - **Propellants**.
  - Commodities (**life support gases**, buffer gases, liquids, etc.).
  - Structural members for construction of telescopes, research facilities, etc.
  - Repair items (tools, parts, etc.)

- Provides additional **raw materials** for:
  - **Bulk radiation shielding**.
  - Construction materials.

- **Excavates** regolith and rock for:
  - Shelters for humans and equipment.
  - Foundations for telescopes, research facilities, etc.
  - Storage capacity for materials and supplies, on surface and underground.

- **Enables** power generation:
  - Materials to produce solar power cells.
  - Materials to produce fuel cell reagents.
  - $^3$He for nuclear fusion reactors.

- **Leverages** initial equipment.
  - Provides these materials for less mass than shipping finished products from Earth.
Additional Assumptions:
- This roadmap may be the basis for future expansion, so the full range of eventual resources is included (gases, liquids, regolith, rock, waste, space, etc.)
- Science Instruments and Sensors Capability will provide all instruments and sensors needed for Resource Assessment and subsequent operations.

Requirements:
- Piggyback Resource Assessment on missions to Moon and Mars
  - Complementary/supplementary to science goals.
  - Assessment provides crucial information for Resource Acquisition, Beneficiation, and Site Management.
- Resource Acquisition requires
  - Power.
  - Dust control.
  - Access – robotic and/or human.
  - Material handling capabilities.
- Resource Beneficiation requires
  - Same as Resource Acquisition, plus well-specified feedstock parameters.
Resource Extraction Commonality-Dependency With Other Capabilities

**Products From Resource Extraction**

- High-Energy Power & Propulsion
  - Power for startup.
  - Mobile/high-density power sources.
- In-Space Transportation
  - Access to Resource Extraction sites.
  - Delivery of products.
  - Delivery of parts, supplies, etc.
- Advanced Telescopes & Observatories
- Telecommunications and Navigation
  - Mobile equipment navigation.
  - Fast communication among systems components.
- Robotic Access to Planetary Surfaces
  - Surface mobility.
  - Robotic access to Resource Extraction sites.
- Human Planetary and Landing Systems
  - Human access to Resource Extraction sites.
- Human Health and Support Systems
  - Enabling human presence on- and near-site.

**Products To Resource Extraction**

- Raw materials for:
  - Propellants.
  - Fuel cell reagents.
  - System components.
  - Infrastructure fabrication.
- Waste re-use.
- Shelter excavation.
- Raw materials for life support.
Resource Extraction Commonality-Dependency With Other Capabilities

Products From Resource Extraction

- Raw materials for:
  - Propellants.
  - Fuel cell reagents.
  - System components.
  - Infrastructure fabrication.
- Increased sample and measurement density for science studies.

Products To Resource Extraction

- Human interfacing with Resource Extraction systems.
- Autonomous and robotic systems for all phases of Resource Extraction.
- Equipment, parts, supplies, etc. delivery.
- Resource Assessment data.
- Resource formation models.
- Mining and reclamation method evaluation.
- Resource delivery and distribution models.
- Granular material performance models.
- Extraction system analyses.
Resource Extraction Interdependency with other ISRU Elements

**ISRU Element Products To Research Extraction**

- **Material Handling & Transportation**
  - Product shipment to customer
  - Supplies delivery

- **Surface Construction**
  - Site preparation
  - Logistics
  - Infrastructure

- **Surface Manufacturing**
  - Spare parts

- **Product Storage & Distribution**
  - Propellants
  - Buffer gases

- **Unique Testing and Certification**
  - Material performance models and tests
  - Equipment/system performance tests

**Resource Extraction**

- **Resource Assessment**
- **Resource Acquisition**
- **Resource Beneficiation**
- **Site Management**

**Products From Resource Extraction**

- **All**
  - Site and region characterization for science and engineering

- **Resource Processing**
  - Feedstock

- **Surface Manufacturing**
  - Feedstock

- **Product Storage & Distribution**
  - Ready-to-use gases and liquids

- **Surface Construction**
  - Ready-to-use construction materials

**Key Assumptions:**
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone

**Capability Roadmap 13: ISRU**

**Polar H₂ Mapping to 5 km**
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated

**Subscale lunar regolith excavation & H₂O extraction**
- Validation of in-situ production of solar electricity

**Mars regolith & H₂O extraction**
- Validation of silicon/metal extraction from lunar regolith

**Lunar O₂ Pilot Plant Capability**
- ISRU science hopper capability

---

### 13.1.1 Resource Assessment
- Mars ISRU demo site
- Lunar demo site(s)
- Mars ISRU subscale site

### 13.1.2 Resource Acquisition
- Lunar regolith acquisition methods demo
- Lunar & Mars sub-scale acquisition methods

### 13.1.3 Resource Beneficiation
- Lunar regolith beneficitation for production of O₂ & metals production
- Mars atmosphere beneficitation
- Mars regolith & H₂O beneficitation
- Lunar regolith beneficitation scale-up

### 13.1.4 Site Management
- Regolith & rock anchoring
- Process monitoring
- Site Planning
- Regolith & rock stability control

---

**Input**
- Lunar Event
- Lunar & Mars Event

**Major Decision**
- Major Event / Accomplishment / Milestone

**Ready to Use**

---

**Timeline:**
- 2005
- 2010
- 2015
Capability Team 13: Resource Extraction Capability Roadmap (2015 to 2035)

**Key Assumptions:**
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone

**Capability Roadmap 3: ISRU**

- Mars Human scale consumable production capability validated
- Mars ISRU full-scale minesite
- Mars deep drilling capability
- Propellant, fuel cell, & life support production for Mars

**13.1.1 Assessment**
- Lunar & Mars full-scale acquisition
- Mars excavation methods
- Mars scale acquisition
- Mars deep drilling
- Mars full-scale atmos. acquisition

**13.1.2 Acquisition**
- Lunar regolith beneficiation full-scale
- Mars regolith & H2O benef. scale-up
- Full-scale Mars regolith beneficiation

**13.1.3 Beneficiation**
- Lunar O2 pilot plant capability
- ISRU science hopper capability
- Mars subscale human propellant production & storage capability

**13.1.4 Site Management**
- Waste management
- Site reclamation

**Timeline:**
- 2015
- 2025
- 2035
Some sub-capabilities have been demonstrated:
- Scooping of regolith samples on the Moon and Mars.
- Coring of regolith samples on the Moon.
- Grinding and analysis of rock samples on the Moon and Mars.
- Mars atmosphere capture and separation
  - Cryo-coolers demonstrated on satellites for long duration (Mars conditions).

The present capabilities of terrestrial Resource Extraction include:
- Semi-automated drilling/boring, fragmentation, excavation, and transportation of rock, both underground and on the surface.
- Semi-automated pre-processing of gases, liquids, and solids into forms suitable for further processing, manufacturing, or direct use.
- Production rates from a few liters/day to 200,000+ tonnes/day.
- Successful operations:
  - from 4,600 m elevation to 3,800 m depth in the crust, and on the sea bottom;
  - in locations accessible only when the ground freezes, when it thaws, or when artificially refrigerated;
  - from the centers of cities to the remote tundra;
  - within and beneath rivers, lakes, and oceans.
## Maturity Level – Capabilities for 13.1 Resource Extraction

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### Maturity Level – Capabilities for 13.1 Resource Extraction

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<tr>
<th>Capability</th>
<th>Key Technologies or Sub-Capabilities</th>
<th>Readiness Assessment</th>
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<td>Mapping Technologies&lt;br&gt;Remote Geophysical Surveying Technologies&lt;br&gt;In Situ Geophysical Survey Technologies&lt;br&gt;Sample Analysis Technologies</td>
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<td>Capability Applications</td>
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<td>Soil &amp; Rock Anchoring Technologies</td>
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Metrics for 13.1 Resource Extraction

- **Performance metrics for**
  - Resource Assessment:
    - Speed of data collection.
    - Speed of data analysis.
    - Accuracy of results.
    - Precision of results.
  - Resource Acquisition, Resource Beneficiation, and Site Management:
    - Material throughput (volumetric or mass flow rate).
    - Production rate of system output.
    - Equipment/system working life.
    - Mean time between component failures.

- **Normalized to:**
  - Launch mass required to initiate.
  - Launch mass required to maintain.
  - Power/energy requirements.
  - Human effort/time required.

- **Performance sensitivity to:**
  - Environmental operating conditions
  - Other operating conditions:
    - Remote-from-tech-support operation
    - Tele-operation
    - Autonomous operation
Funding in Place for 13.1 Resource Extraction

- **Regolith Characterization Instrument Suite**
  - USACE Cold Regions Research and Engineering Lab, Honeybee Robotics, Applied Research Assoc, University of Arizona, Los Alamos National Lab, several NASA Centers

- **Lunar Construction Equipment Concepts**
  - Caterpillar, Honeybee Robotics, Dartmouth College, several NASA Centers

- **Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE)**
  - Northern Center for Advanced Technology, Colorado School of Mines, Lockheed-Martin, Boeing, Orbitec, several NASA Centers

- **ISRU for Human Exploration - Propellant Production for the Moon and Beyond**
  - Lockheed-Martin

- **current SBIR projects:**
  - Low-energy Planetary Excavator (LPE), Orbitec
  - Sample Acquisition for Materials in Planetary Exploration (SAMPLE), Orbitec
Gaps and Risks for 13.1 Resource Extraction

- **Gaps:**
  - Products and target materials – better definition required:
    - Extraction method depends on detailed resource information.
    - Extraction and beneficiation also depend on detailed product specifications.
  - Current data useful only for prospecting – better resolution required.
  - Unknown mass/mission constraints – precise architecture required.
  - Lunar and martian granular materials behavior poorly understood.
  - Effects of lunar and martian environments on equipment technologies:
    - Required capabilities are common to all environments.
    - Only the technologies needed to achieve these capabilities vary.

- **Risks:**
  - Prospecting uncertainty: "You don't know what you're dealing with until you already have."
  - System reliability.
  - Effects of lunar and Mars environmental conditions.
  - Political uncertainty.
  - Terrestrial experience in resource extraction is broad and deep, but translating these capabilities to the ISRU mission is new.
ISRU Capability Element 13.2
Material Handling and Transportation

Presenter:
Kurt Sacksteder/NASA GRC
Dale Boucher/NORCAT
Co-Chairs
Kurt Sacksteder, NASA Glenn Research Center
External: Dale Boucher, Northern Centre for Advanced Technology

Government: NASA
- Allen Wilkinson, GRC

Government: Other
- Darryl Calkins, Sally Shoop, Peter Smallidge, & Jerry Johnson; USACE Cold Regions Research & Engineering Lab

Industry
- Jim Richard, Northern Center for Advanced Technology
- Klaus Heiss, High Frontier
- Larry Clark, Lockheed Martin Corp.

Academia
- Leslie Gertsch, University of Missouri, Rolla
- Brad Blair, Colorado School of Mines
The Material Handling and Transportation sub-element describes capabilities for the handling of native resource materials within and transportation between ISRU devices

- Including devices for the harvesting, processing, inter-stage transfer and storage of these materials,
- including raw and beneficiated resources, and intermediate and final product materials that may be solid, liquid, vapor or multi-phase.

This capability addresses the challenging environments of space

- Lunar partial gravity, hard vacuum, temperature extremes, etc.
- Martian partial gravity, low atmospheric pressures and temperatures, wind, dust etc.
- Asteroids, Phobos, Deimos, “micro” gravity, hard vacuum, temperature extremes.
Attributes
13.2 Material Handling and Transportation

- Short distance movement of materials using fixed devices including augers, conveyors, cranes, plumbing, pumps, etc.

- Long distance movement of materials using surface vehicles including wheeled, tracked or rail-based; flight vehicles including aircraft or rocket propelled hoppers; plus the roads or other infrastructure needed for them.

- Resource material in various stages of added value including raw resources (regolith, atmosphere, etc.) and intermediate to finished products (cryogenic propellants, I-beams, etc.); materials requiring environmentally-controlled containment; and materials whose movement may be affected by the cold/vacuum/low-gravity space environment.

- Cross platform features including power and fueling; mechanisms and container seals; sensors and artificial intelligence; and strategies for logistics and system reliability.
The capabilities in this sub-element will enable:

- Manipulation of ISRU materials independent of the specific technology chosen for resource collection, processing, or storage.

- Collecting and processing quantities of resource materials beyond the capability of a small integrated demonstration device.

- Independent siting of resource collection, processing, storage and customer assets.

- Establishment of human or robotic operations at desirable Lunar and Martian surface locations independent of the location of essential in-situ resources.
13.2 Material Handling & Transportation

- Capabilities in MH&T are introduced over time according to the ISRU-Intensive Mission Architecture:
  - Demonstrations: Integrated systems – primarily material handling
  - Early operations: Material handling and local transportation
  - Later operations: Material handling and long-range transportation

- Substantial “High Energy Power…” is needed before ISRU produced surface power is available. ISRU is eventually self-sufficient, then delivers power system consumables to customers.

- Mobile transportation requires substantial “…Surface Mobility” capability for common vehicle chassis and ISRU compatible motive power.
  - MH&T provides specific functional capability on the common chassis.
  - ISRU eventually delivers fuel to surface mobility customers.

- MH&T capability includes “material handling” for other ISRU elements.

- This element supports the delivery of stored ISRU products (e.g. cryogenic propellants) in coordination with ISRU sub-element 13.6.
Material Handling and Transportation Commonality-Dependency With Other Capabilities

**Products From** Material Handling & Transportation

- Delivery and transfer of:
  - Propellants/oxidizer
  - Life support consumables and buffer gases
  - Fuel cell reagents
  - Logistics system

**Products To** Material Handling & Transportation

- High-Energy Power & Propulsion
  - Power to startup short and long distance transport and environmental control in shipping containers.
  - ISRU fuel compatible power/prop. sys.

- In-Space Transportation
  - Delivery of MH&T assets (infrastructure, parts and supplies.)
  - Delivery in space of ISRU products.
  - ISRU propellant compatible systems

- Advanced Telescopes & Observatories
  - Vehicle location and navigation
  - Low bandwidth command and control

- Telecommunications and Navigation
  - Pre-positioning of MH&T assets
  - ISRU fuel compatible power/prop. sys

- Robotic Access to Planetary Surfaces
  - Pre-positioning of MH&T assets
  - ISRU fuel compatible power/prop. sys.

- Human Planetary and Landing Systems
  - ISRU compatible air/water/solid reclamation/recycling systems

- Human Health and Support Systems
  - ISRU compatible air/water/solid reclamation/recycling systems

Capability Dependency

- Hi Criticality
- Med Criticality
- Lo Criticality

Gerald B. Sanders/JSC, gerald.b.sanders@nasa.gov
### Products From Material Handling & Transportation

- Delivery and transfer of:
  - Propellants/oxidizer
  - Life support consumables and buffer gases
  - Fuel cell reagents
  - Logistics system
- Mobility and in-situ data resource
- Models, simulations, & engineering data of material behavior in low temperature/pressure/ gravity
- Logistics of terrestrial MH&T system operations

### Products To Material Handling & Transportation

- Reconfigurable transportation platforms compatible with ISRU Ops.
- ISRU fuel compatible power/prop. sys.
- Autonomous and robotic systems for many aspects of MH&T.
- ISRU fuel compatible power/prop. sys.
- Delivery of MH&T infrastructure, parts and supplies.
- ISRU fuel compatible power/prop. sys.
- Transportation hazard identification.
- MH&T device status/integrity (pipes, roads, rail, augers, containers, etc.)
- Model/simulate material behavior in low temperature/pressure/ gravity (granular media, multiphase fluid, etc.)
- Logistics of MH&T system operations
- Strategies for scaling up operation capability
- Low temp/press lubricants
Material Handling and Transportation Interdependency with other ISRU Elements

**ISRU Element Products To Material Handling and Transportation**

- **Resource Extraction**
  - Material Handling and Transportation Requirements
  - Compatible Material Transfer Interfaces

- **Resource Processing**
  - Material Handling and Transportation Requirements
  - Compatible Material Transfer Interfaces

- **Surface Manufacturing**
  - Spare parts

- **Surface Construction**
  - Road Building
  - Infrastructure

- **Product Storage & Distribution**
  - Cryogenic Fluid Transportation Containment and Equipment
  - Compatible Material Transfer Interfaces

- **Unique Development and Certification**
  - Equipment/system performance tests in relevant environments

**Material Handling and Transportation**

- **Fixed Site Transportation**
- **Mobile Material Transportation**
- **Payload Material Handling**
- **Cross Platform Capabilities, Reliability and Logistics**

**Products From Material Handling and Transportation**

- **Resource Extraction**
  - Material Handling Capability
  - Delivery of extracted feedstock

- **Resource Processing**
  - Material Handling Capability
  - Delivery of Processing Feedstock
  - Delivery of Processing Products

- **Surface Manufacturing**
  - Delivery of Manufacturing Feedstock
  - Delivery of Manufactured Products

- **Surface Construction**
  - Delivery of Construction Feedstock

- **Product Storage & Distribution**
  - ISRU product delivery to storage
  - Mobile product delivery to user

- **Unique Development and Certification**
  - Testing Requirements

- **All ISRU Elements**
  - ISRU Resource and Product Logistics
  - Fuel, supplies and parts delivery

Key Assumptions:
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone

Capability Roadmap 13: ISRU
- Polar H₂ Mapping to 5 km
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated
- 0-g manufacturing & repair demonstrated
- Subscale lunar regolith excavation & O₂ production & storage
- Lunar O₂ Pilot Plant Capability
- Subscale Mars regolith excavation & H₂O extraction
- ISRU Science Hopper capability

13.2 Material Handling and Transportation
- Fixed Site Transp.
  - Carrier Concept
  - Local Transfer of Excavated Regolith to Processing TRL 6
- Mobile Mat'l. Transp.
  - Carrier Concept
  - Short haul Regolith Transfer, Fueling TRL 6
- Payload Mat'l. Handling
  - Granular media emphasis TRL 6
  - Reacting media emphasis TRL 6
  - "All" TRL 6
- Cross Platform Capability, Reliability and Logistics
  - Mechanism and Actuators Demo in Low Temp/Press/Gravity
  - Low Temp/Dusty Seals/Lubrication TRL 6

ISS Related Capability Milestone
Moon Related Capability Milestone
Mars Related Capability Milestone

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<th>2010</th>
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**Key Assumptions:**
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone

**2015 - 2035**

- **2015:**
  - Lunar O₂ Pilot Plant Capability
  - ISRU science hopper capability
  - Mars subscale human propellant production & storage capability

- **2020:**
  - Mars Human scale consumable production capability
  - Mars deep drilling capability
  - Mars in-situ bio support capability validated

- **2025:**
  - Propellant, fuel cell, & life support production for Mars

**13.2 Material Handling and Transportation**

13.2.1 Fixed Site Transp.
- Carrier Concept

13.2.2 Mobile Mat'l. Transp.
- Carrier Concept

13.2.3 Payload Mat'l Handling
- Material Transport Container

13.2.4 Cross Platform Capab., Reliability and Logistics
- Reliability and Logistics

**Autonomous Transportation and Containment of ISRU Propellant and Life Support Consumables**

- Carrier Concept

**ISS Related Capability Milestone**
- **2015**
- **2025**
- **2035**

**Moon Related Capability Milestone**
- **2015**
- **2025**
- **2035**

**Mars Related Capability Milestone**
- **2015**
- **2025**
- **2035**
Current State of the Art:  
13.2 Material Handling & Transportation

- **Extra-terrestrial experience in handling and transporting native materials is very limited:**
  - Apollo samples were manually manipulated for encapsulation and return to Earth. Considerable problems with dust and seals stays.
  - Some Apollo samples were transported in small containers aboard the Lunar rover vehicle.
  - Martian surface samples were/are robotically manipulated for limited analysis and disposal, Viking, MER, etc.

- **Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge:**
  - Terrestrial handling of granular media is largely empirical and may not be scalable – reduced gravity, temperature and pressure; abrasive lunar regolith will amplify the uncertainties.
  - Technology for handling materials in ways that would be affected by the gravity level (e.g. multi-phase and non-isothermal fluids) has been largely avoided in space-based systems.
  - Operational approach to power consumption, reliability, logistics, etc. requires blending terrestrial experience with space realities.
## Maturity Level
### 13.2 Material Handling and Transportation

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### 13.2 Material Handling and Transportation

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# Maturity Level

## 13.2 Material Handling and Transportation

### Payload Material Handling

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### Maturity Level

#### 13.2 Material Handling and Transportation

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MH&T Capability meets quantitative requirements of customers, e.g:
- ISRU: Resource Extraction, Resource Processing, and Resource Storage and Distribution (Mass throughput, reliability, etc.)
- Other: High Energy Power/Prop, Human Exploration/Surface Mobility, Robotic Systems

Function and Reliability in the space environment
- Redundancies established at the parts through system levels by the time of pilot plant capability demonstration
- Mean failure rate less frequent than Earth replacement possibility
- Power consumption less than 10% of total ISRU system in place
- Capacity growth ahead of Resource Extraction growth
- Logistics and Reliability system capability is semi autonomous by the time of pilot plant capability demonstration

MH&T systems meet Total Throughput Mass/System Mass targets
- <1 for early demonstrations
- 10x for pilot plant demonstrations
- 1000’s x for operational systems

Each of these metrics is measurable directly or in comparison with parallel capability developments
- Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE)
  - Integrated material handling demonstration
- ISRU excavation project
  - Integrated material handling demonstration
- Dust Mitigation
  - Characterization and mitigation of very small regolith particles
- Isolated studies from the former NASA Physical Sciences Division
  - Characterizations of reacting systems, multi-phase flows, and granular media behavior in variable gravity environments.
The principal gaps in MH&T capability stem from the fact that material handling techniques in the Lunar/Martian environment cannot be extrapolated from extensive Terrestrial experience:

- Handling of granular media in terrestrial environments is accomplished by engineering based largely upon experience, not fundamental principles.
- Processes involving multi-phase, non-isothermal, or reacting fluids are affected by changes in gravitation level in ways that are predictable in only a few limited cases.
- Energy intensive thermal and chemical processes requiring reliable mechanisms, seals, etc. have not been demonstrated.

It follows that the principal risks lie in development efforts limited to Terrestrial environments which may lead to failures in deployed systems designed to operate autonomously for extended periods.

A risk mitigating strategy requires early effort to establish fundamentally based design guidance for the operational environment.
ISRU Capability Element 13.3
Resource Processing

Interim Roadmap Status Report
Presenter:
William E. Larson
Co-Chairs
NASA: William E. Larson, NASA
External: D. Larry Clark, Lockheed Martin Astronautics

NASA
- Tom Cable
- Bob Green
- Chi Lee
- Diane Linne
- Dr. Dale E. Lueck
- Dr. Clyde Parrish
- Margaret Proctor
- Kurt Sacksteder
- Tom Simon
- Stephen Sofie
- Dr. Bruce Steinetz
- Tom Tomsik
- Judy Yen

Industry
- Ed McCullough, Boeing
- Eric Rice, Orbitec
- Dr. Laurent Sibille, BAE Systems
- Dale Taylor, Jim Stepan, Ceramatec
- Robert Zubrin, Pioneer Astronautics

Academia
- Dr. Robert Ash, Old Dominion University
- Brad Blair, Colorado School of Mines
- Kriston Brooks, Battelle Memorial Institute
- Dr. Christine Iacomini, University of Arizona
- David C. Lynch, Sc.D, University of Arizona
Capability 13.3: Resource Processing

- Resource Processing Is The Set Of Capabilities Needed To Convert Raw Materials Found At An Exploration Destination In To Usable Products.

- Three Product Classes
  - Mission Consumables (e.g. Oxygen, Fuel, Purified Water, Fertilizer…)
  - Feedstock for Manufacturing (e.g. Metals, Silicon, Plastics…)
  - Feedstock for Construction (e.g. Bricks, Glass, Fiberglass…)

- Resource Processing Receives It’s Raw Materials From The Extraction And Transportation Elements.

- Resource Processing Will Deliver It’s Finished Products To Either The Storage And Distribution (gases/liquids) Or Transportation Elements (barstock, I-beams, powdered metals)
Benefits of Resource Processing

- Consumable Production Provides The Exploration Mission Significant Mass Savings.
  - Propellant and Oxygen Production Reduces Mass Between 3.5:1 And 5:1 On Human Mars Mission Depending On The Architecture.
  - e.g. ISS Required **2250 kg of Water This Year** To Provide Oxygen to Breathe And Water To Drink For An Average Crew Of 2.5

- Consumable Production Provides Overall Program Cost Reduction
  - Reduced Size Of Launch Vehicle Or Reduced Number Of Launches
  - Allows For The Development Of Reusable Transportation Assets

- Consumable Production Long Duration Robust Surface Mission Mobility
  - O2/H2 Production Allows Use Of Fuel Cell-based Refuelable Rovers
  - Habitat Life Support

- Provides An In-Situ Source Of Feedstocks For Manufacturing
  - Reduces Earth-based Logistics & Improves Safety.

- Enables Architectures That Would Otherwise Be Unattainable
- Enables Space Commercialization
Resource Processing

Mission Consumable Production
13.3.1

Oxygen Production
13.3.1.1

Propellant & Fuel Cell Reagent Production
13.3.1.2 thru 13.3.1.8

Water Purification
13.3.1.9

Buffer & Science Gas Production
13.3.1.10 & 13.3.1.11

Bio-Support Feedstock Production
13.3.1.12

Feedstock Production for In-Situ Manufacturing
13.3.2

Chemical Regolith Beneficiation & Carbon Production
13.3.2.1 & 13.3.2.2

Metal Feedstock Production (iron, aluminum, alloys, etc.)
13.3.2.3 thru 13.3.2.5

Glass/Ceramic Feedstock Production (Silicon)
13.3.2.6 thru 13.3.2.8

Polymer/Plastic Feedstock Production
13.3.2.9

Feedstock Production for Surface Construction
13.3.3

Concrete/Bricks
13.3.3.1

Fiberglass
13.3.3.2

Common Critical Components
13.3.4
Resource Processing

In-Situ Resource Utilization

Resource Processing

Mission Consumable Protection
13.3.1

Feedstock Production for In-Situ Manufacturing
13.3.2

Feedstock Production for Surface Construction
13.3.3

Oxygen Production
13.3.1.1

Hydrogen Reduction of Regolith
13.3.1.1.1

Carbothermal Reduction
13.3.1.1.2

Molten Regolith Electrolysis
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Molten Salt Electrolytic Reduction of Regolith
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Hydrogen Extraction
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Carbochlorination Reduction of Regolith
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Hydrofluoric Acid Leach
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Water Electrolysis
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Solid Oxide CO2 Electrolysis
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Ionic Liquid CO2 Electrolysis
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Molten Carbonate CO2 Electrolysis
13.3.1.1.11

Sabatier Reactor
13.3.1.1.12

Reverse Water Gas Shift
13.3.1.1.13

Cold Plasma CO2 Disassociation
13.3.1.1.14
Team Assumptions for Resource Processing

- Reusable Landers Will Land “Empty” And Be Refueled On The Surface
- Surface Mobility Systems Will Utilize In-Situ Produced Fuel Cells Reagents
- Long Term Missions Will Require The Production Of Manufacturing Feedstocks
- Permanent Presence On Other Planetary Bodies Will Require The In-Situ Production Of Construction Materials
- ISRU Systems Will Generally Be Predeployed By Robotic Missions And Will Operate Autonomously For Up to 500 days
- Robotic Mars Sample Return Missions (Direct Earth Return) Will Require The Production Of 1500kg Of Propellant
- Robotic Mars Sample Return (Orbital Rendezvous) Require 300kg Of Propellant
- Human Lunar Ascent Vehicles Will Require 20-30 Metric Tons Of Propellant
- Human Mars Ascents Vehicles Will Require ~50 Metric Tons Of Propellant
- Power systems will be available to supply the needs of ISRU systems even in the permanently shadowed craters of the moon.
### Resource Processing Interdependency with other Capabilities

#### Products From Resource Processing
- Propellant production
- Fuel Cell Reagents
- Propellant production and pressurant/purge gases for lander reuse and in-space depots
- Gases for Inflatable Structures
- Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions)
- Propellant production for surface hoppers or large sample return missions
- Materials for Landing pads/plume debris shielding
- Propellant production for lander reuse

#### Capability Products To Resource Processing
- Solar & nuclear power to support power-intensive ISRU activities
- ISRU-compatible propulsion
- Electromagnetic launch systems for delivery of ISRU products
- Pre-positioning & activation of ISRU assets
- Delivery of ISRU capabilities to sites of exploration

---

**High-Energy Power & Propulsion**

**In-Space Transportation**

**Advanced Telescopes & Observatories**

**Robotic Access to Planetary Surfaces**

**Human Planetary Landing Systems**
Resource Processing Interdependency with other Capabilities

**Products From Resource Processing**
- Gases for inflation & buffer gases
- Life support consumable production for backup
- Fertilizer for plant growth
- Materials for in-situ manufacturing
- O\(_2\) production for EVA & Gases for science equipment
- Propellants & fuel cell reactants for surface vehicles and aero-bots

**Capability Products To Resource Processing**
- Carbon-based waste products as resource for ISRU
- Crew/robotics/rovers to perform ISRU surface activities
- ISRU Compatible Robots/rovers Software & FD&R logic for autonomous operation
- Resource location & characterization information
- Self Calibrating or Extended Calibration Life Sensors
- Nanotube catalysts for Microchemical Reactors

- Human Health and Support Systems
- Human Exploration Systems & Mobility
- Autonomous Systems & Robotics
- Scientific Instruments & Sensors
- Nano-Technology
Resource Processing Interdependency with other ISRU Elements

**ISRU Element Products To**

**Resource Extraction**
- Regolith Excavation & Physical Beneficiation
- Regolith Volatiles Collection & Separation
- Atmospheric Gas Acquisition & Separation

**Resource Transportation**
- Surface mobility systems platforms for Raw Resource Transportation
- Surface mobility systems for Finished Product Utilization

**Surface Manufacturing w/ In-Situ Resources**
- Spare Parts for Resource Processing Systems
- Energy From PV Arrays

**Product Storage & Distribution**
- Stored Gases/Liquids as inputs to Resource Processing

**Resource Processing**

**Feedstock**

**Manufacturing Feedstock**

** Consumables**

**Products From Resource Processing**

**Product Storage & Distribution**
- Oxygen for Life Support
- Oxygen for Propulsion
- Oxygen for Fuel Cells
- Fuels for Propulsion
- Hydrogen/Methane for Fuel Cells
- Buffer Gasses for Life Support
- Water for Life Support
- Ammonia for Cooling Systems

**Surface Manufacturing w/ In-Situ**
- Iron, Carbon Steel, Titanium & Aluminum for Manufacturing
- Carbon
- Plastics for Parts Manufacture
- Silicon for Electronics and Photovoltaic Arrays
- Glass for PV arrays

**Surface Construction**
- Ceramics for Construction Materials Fab (e.g. Bricks)
- Iron, Aluminum, and Steel for Habitat Construction
- Fiberglass for Composite Construction Materials
- Slag for Bricks
- Slag for Habitat Radiation Protection
- Slag for Nuclear Reactor Shielding

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov
13.3.1 Mission Consumable Production

13.3.2 Feedstock Production for In-Situ Manufacturing

13.3.3 Feedstock Production for Surface Construction

13.3.4 Common Critical Components

Key Assumptions:

- ISS
- Moon
- Mars

Capability Roadmap 13: ISRU

- Polar H₂ Mapping to 5 km
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated
- 0-g manufacturing & repair demonstrated

Lunar Oxygen Production

- Lunar O₂ Pilot Plant Capability

Propellant and Fuel Cell Reagent Production

- Validation of in-situ solar electricity production

Chemical Regolith Beneficiation & Carbon Production

- Validation of silicon/metal extraction from lunar regolith

Mare/HL (5 kg/hr)

- Validation of silicon/metal extraction from lunar regolith

Buffer and Science Gas Production

- ISRU science hopper capability

Fabric Production

- ISS = ISS
- = Human Mission
- = Robotic or Predeployed ISRU mission
- = Major Event/Accomplishment/Milestone
- = ISS
- = Moon
- = Mars

2005  2010  2015
Current State-of-the-Art for Resource Processing

- Lunar ISRU Has A 30 Year History Of Laboratory Testing, But Little Development Money For Systems Level Development.
  - Majority Of Historical Work Is In O2 Production With Metals As A Byproduct Current TRL Is 3 At Best.
  - Reasonable Amount Of Research Has Been Conducted In The Production Of Silicon For Photovoltaic Arrays And Ceramics For Manufacturing But TRL For A Lunar Environment Still Low.

- Mars ISRU Has Had More Development Over The Last Decade But Focus Has Been Atmospheric Processing
  - O2 & Fuel Production CRL Estimate is between 2 and 3.
  - Several Technologies Have Been Developed As Sample Return-Scale Breadboards
    - RWGS, Sabatier, Solid Oxide Electrolysis, Methanol, Benzene
  - One Flight Experiment Has Been Developed, But Has Not Yet Flown
    - Mars In-Situ Propellant Production Precursor
  - Mars Metals Production At A Very Low TRL, But Will Share Reasonable Commonality with Lunar ISRU.
## Maturity Level – Capabilities for Resource Processing

<table>
<thead>
<tr>
<th>Capability</th>
<th>Key Technologies or Sub-Capabilities</th>
<th>Capability Readiness Assesment</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>CRL</td>
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<tr>
<td><strong>Mission Consumables Production</strong></td>
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<td>Methanol Production</td>
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<td>Nitrogen Production</td>
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<td>Argon Production</td>
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<td>Plastics</td>
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## Capability Readiness Assesment

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<td>Feedstock for Construction</td>
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<td>Common Critical Components</td>
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<td>Reaction Chamber Seals for High Vacuum, Dusty Environments</td>
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<td>Product Shaping (Ingots, Bar Stock, Powdered Metal)</td>
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<td>High Efficiency Gas Separation</td>
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<td>Oxygen Purification</td>
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<tr>
<td>Technology</td>
<td>Capability Applications</td>
<td>Readiness Assesment</td>
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<tr>
<td>Hydrogen Reduction of ilmenite</td>
<td>Oxygen Production, Iron Production</td>
<td>TRL 4, R&amp;D 3</td>
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<td>Carbothermal Reduction of Regolith</td>
<td>Oxygen Production, Iron Production</td>
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<td>Molten Regolith Electrolysis</td>
<td>Oxygen &amp; Metal Production</td>
<td>TRL 2, R&amp;D 5</td>
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<td>Molten Salt Electrolytic Reduction of Regolith</td>
<td>Oxygen, Iron, Aluminum, Titanium, Silicon Production</td>
<td>TRL 4, R&amp;D 3</td>
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<td>Carbochlorination reduction of anorthite and ilmenite</td>
<td>Oxygen Production</td>
<td>TRL 2, R&amp;D 4</td>
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<td>Hydrofloric Acid Leach</td>
<td>Oxygen Iron, Silicon, Aluminum, Titanium &amp; Glass Production</td>
<td>TRL 3, R&amp;D 3</td>
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<td>Solid Oxide CO2 Electrolysis</td>
<td>Oxygen &amp; Carbon Monoxide Production</td>
<td>TRL 4, R&amp;D 3</td>
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<td>Ionic Liquid CO2 Electrolysis</td>
<td>Oxygen, Carbon Monoxide &amp; Carbon Production</td>
<td>TRL 1, R&amp;D 4</td>
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<td>Molten Carbonate CO2 Electrolysis</td>
<td>Oxygen, Carbon Monoxide &amp; Carbon Production</td>
<td>TRL 3, R&amp;D 4</td>
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<tr>
<td>Cold Plasma CO2 Disassociation</td>
<td>Oxygen, Carbon Monoxide Production</td>
<td>TRL 3, R&amp;D 4</td>
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<td>Sabatier Reactor</td>
<td>Oxygen &amp; Methane Production</td>
<td>TRL 5, R&amp;D 4</td>
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<tr>
<td>Reverse Water Gas Shift</td>
<td>Oxygen, Water &amp; Carbon Monoxide Production</td>
<td>TRL 4, R&amp;D 4</td>
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<td>Hydrocarbon Reformer</td>
<td>Hydrogen Production</td>
<td>TRL 4, R&amp;D 4</td>
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<td>Liquid Water Electrolysis</td>
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<td>Gas Phase H2O Electrolysis</td>
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<td>Methanol Reactor</td>
<td>Methanol Production</td>
<td>TRL 4</td>
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<tr>
<td>Fischer-Tropsch Reactor</td>
<td>Ethylene &amp; Plastics Production</td>
<td>TRL 3, R&amp;D 4</td>
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**Maturity Level – Technologies Resource Processing**
## Technology Maturity Level

### Resource Processing

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capability Applications</th>
<th>TRL</th>
<th>R&amp;D</th>
<th>Need Date</th>
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<td>I</td>
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<td>Deionization Bed</td>
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<td>Distillation</td>
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<tr>
<td>Reverse Osmosis</td>
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<td>Gas Separation Membranes</td>
<td>Nitrogen, Argon &amp; Carbon Monoxide Production</td>
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<td>Cryogenic Gas Separation</td>
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<td>Catalytic Decomposition of CO</td>
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<tr>
<td>Hydrochloric Acid Leach</td>
<td>Iron, Aluminum, Silicon, Glass</td>
<td>4</td>
<td>II</td>
<td>2014</td>
</tr>
</tbody>
</table>
Metrics for Resource Processing

- Summary of Resource Processing Metrics For Technology Trades
  - Rate of Production
  - Power Consumed vs. Mass of Product Produced
  - Mass of System vs. Mass of Product Produced
  - Mean Time Between Failure
  - Degree of System Autonomy
  - Reagent Recycling Near or At 100%

- Summary of Progress Metrics
  - All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
  - All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
  - Continuous Operation for 30 days 5 years before need date.
  - Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date
Current Resource Processing Projects

- Microchannel In Situ Propellant Production System,
  - Battelle Memorial Institute, Richland, Washington
  - NASA: JSC, GRC; Oregon St. Univ., Colorado School of Mines
  - Methane and Oxygen Production from CO2

- ILMENOX,
  - British Titanium, London, England,
  - NASA: KSC; Florida Institute of Technology (FIT)
  - Oxygen Production from Lunar Regolith

- Integrated In-Situ Resource Utilization for Human Exploration – Propellant Production for the Moon and Beyond,
  - Lockheed Martin Astronautics, Littleton, Colorado
  - NASA: JSC, GRC, KSC; Hamilton Sunstrand, CO School of Mines, FIT, ORBITEC

- RESOLVE: Development of a Regolith Extraction & Resource Separation & Characterization Experiment for the 2009/2010 Lunar Lander,
  - NASA JSC, KSC, GRC, JPL; CO School of Mines, NORCAT, Boeing, ORBITEC
  - Lunar Oxygen Production & Hydrogen Extraction Experiment
    - Also supports Resource Extraction Sub-element
Technology Gaps for Resource Processing

- Reduction Of System Size, Microchannel Reactors Seem To Hold Great Promise
- Solid Oxide Electrolysis Of CO2 Struggles With Temperature Cycling Issues, Development A Workable Seal Between The Cell Stacks Is A Challenge That Must Be Met
- Systems Require The Development Of Seals That Can Work Repeatedly In A Low Temperature, High Vacuum, Abrasive Dust Environment.
- Many Of The Processes Involve Molten Materials, Designs To Handle This Molten Material Autonomously Are Not Trivial Exercises
- Improved Energy Efficiencies
- Understanding Of Reduced Gravity Effects On Processes
- Mixed Gas Stream Separation
- Chunks Of Pure Metals Have Been Produced, But They Are “Frozen” In The Slag, Not Separated Out.
- Significant Work Remains To Develop The Integrated Systems That Will Produce Final Feedstocks
There is no one "best solution" for resource processing.

- One technology may trade better than another depending on the architecture.

As architecture options mature, trade studies will be used to down select to a set of technologies that have the potential to meet mission requirements.

These technologies will be developed to TRL 5, and another down selection will occur.

- Performance metrics and mission requirements will be the determining factor.

The suite of technologies will be flight tested on robotic precursor missions to validate the capabilities and readiness for insertion into the critical path for human missions.
Surface Manufacturing with In Situ Resources Element: ISRU Capability Roadmap Progress Review

Peter A. Curreri - NASA Lead
Edward D. McCullough – Boeing, External Lead
April 12, 2005
Surface Manufacturing with In Situ Resources Team

Team 13: In-Situ Resource Utilization

Co-Leads

NASA: Peter A. Curreri, NASA/MSFC
External: Edward D. McCullough, Boeing

Government:

- Ken Cooper, NASA MSFC
- Peter Curreri, NASA MSFC (Co-Lead 13.4.4)
- Melanie Bodiford, NASA MSFC
- Kevin McCarley, NASA MSFC
- Richard Hagood, NASA MSFC
- Ron King, NASA MSFC
- Lee Morin, State Department
- Mark Nall, NASA MSFC

NASA on-site contractors:

- Daniel Jett, TBE, MSFC
- Scott Gilley, Tec-Masters, MSFC
- Jim Kennedy, TBE, MSFC
- Charles Owens, TBE, MSFC
- Julie Ray, TBE, MSFC (Lead 13.4.1,2,3,6)
- Fred Rose, BD Systems, MSFC
- Yancy Young, TBE, MSFC

Industry

- Gary Rodriguez, sysRAND Corp. (Co-Lead 13.4.1,2,3,6)
- Takashi Nakamura, Physical Sciences Inc.
- Charles O’Dale, Senomix Software
- Eric Rice, ORBITEC
- Rich Westfall, Galactic Mining
- Mark W. Henley, Boeing
- Edward McCullough, Boeing (Lead 13.4.5)
- David A. Rockwell, Raytheon
- Patricia Downing, Bechtel BSII Construction
- Nick Anstine, Bechtel BSII Construction
- Ronald Davidson, Guigne

Academia

- Allen Crider, U. of North Dakota
- Alex Ignatiev, U. of Houston (Lead 13.4.4)
- Ted Loder, Univ. New Hampshire
- John Moore, CSM
- Brad Blair, Colorado School of Mines
- Marvin E. Criswell, Colorado State University
- Mike Gaffey, Space Studies Department University of North Dakota
Surface Manufacturing with In Situ Resources is a set of capabilities which enable repair, production of parts and integrated systems on the Moon and beyond using in situ resources.

Six Surface Manufacturing Sub Capabilities are:
- Additive Manufacturing (e.g. Free Form, Composites, CVD …)
- Subtractive Manufacturing (e.g. Machining, E-Beam of Laser Cutting …)
- Formative Manufacturing (e.g. Casting, Extrusion, Sintering, SHS …)
- Locally Integrated Energy Systems (e.g. Photovoltaic Arrays, Solar Concentrators, Power Beaming, Power Storage …)
- Locally Integrated Systems (e.g. Precision Assembly and Joining …)
- Manufacturing Support Systems (e.g. Non Destructive Evaluation and Metrology)

Surface Manufacturing receives it’s feedstock (barstock, I-beams, powdered metals) from the Resource Processing and with support from Transportation.

Surface Manufacturing extends repair and spare parts services to all surface operations. It delivers expandable power for in situ resource extraction and processing, surface construction, and manufacturing.
Benefits of Manufacturing with In Situ Resources

- **In Situ Repair and Spare Parts Manufacturing**
  - Enables the development of safe, self-sufficient, self-sustaining systems on the Moon and beyond.
  - Enables safe and timely recovery from system failures using in situ versatile manufacturing techniques (with design files from Terrestrial Design Centers) without long and expensive logistics from Earth.

- **In Situ Manufacturing with In Situ Resources**
  - Industrial Plant capable of manufacturing product mass orders of magnitude beyond the mass of the facility
  - Industrial Plant capable of manufacturing a second-generation Industrial Plant almost entirely (80% - 95%) from ISRU sources

- **Surface Manufacturing of In Situ Energy Systems**
  - Develop energy-rich environment in Space
  - Energy systems on the Moon and beyond to be expended for decreased cost for Increased production. For example a 1 MW solar cell system can be produced on the Moon with in situ resources for 1/10th the launch mass as a non in situ system.

- Enables large scale Space Commercialization and Development and safe low cost Human Exploration.
Surface Manufacturing with In Situ Resources

- Additive, Subtractive, Formative, Manufacturing
- Locally Integrated Energy Systems
- Locally Integrated Systems and Components
- In Situ Derived Products
## Resource Processing Interdependency with other Capabilities

### Products From Surface Mfg & Resources
- Solar array and collector manufacturing & assembly
- Rectenna fabrication for orbital power beaming
- Thermal storage material production & fabrication
- Parts and components for Lunar infrastructure
- Repair/replacement of reflector coatings
- Shaping crater for collector
- Power availability from ISRU fabricated solar cells
- Power beaming for power to robots
- Repair, replace and fabricate system components
- Energy rich environment from ISRU fabricated solar cells
- Materials for in-situ manufacturing
- Spare parts produced on demand for mobility systems
- Energy rich environment from ISRU fabricated solar cells
- Power beaming for power to robots
- Energy rich environment from ISRU fabricated solar cells

### Capability Products To
- Solar & nuclear power to support power-intensive ISRU activities
- Resource location & characterization information
- Surface mobility system design & experience
- Pre-positioning & activation of ISRU assets
- Precision landing
- Delivery of ISRU capabilities to sites of exploration
- Carbon-based waste products as resource for ISRU
- Crew/robotics/rovers to perform ISRU surface activities
- Robots/rovers to perform ISRU surface activities
- Software & FDIR logic for autonomous operation
- Resource location & characterization information

---

### In-Situ Resource Utilization
- **High-Energy Power & Propulsion**
- **In-Space Transportation**
- **Advanced Telescopes & Observatories**
- **Robotic Access to Planetary Surfaces**
- **Human Planetary Landing Systems**
- **Human Health and Support Systems**
- **Human Exploration Systems & Mobility**
- **Autonomous Systems & Robotics**
- **Scientific Instruments & Sensors**
ISRU Element Products To Surface Manufacturing

- **Resource Transportation**
  - Surface mobility systems platforms for Raw Resource Transportation to In Situ Manufacturing
  - Mobile Material Transportation for Manufacturing

- **Resource Extraction**
  - Feedstock for In Situ Manufacturing
  - Metals, alloys, ceramic, and glass stock materials

- **Product Storage & Distribution**
  - Stored Materials for Surface Manufacturing

- **Locally Integrated Energy Systems**
  - Energy for In Situ Manufacturing

---

**Surface Mfg and Resources**

- Manufacturing Spare (iron, carbon, Al, Carbon, Titanium, Alloy, Plastic, glass etc.) Parts
- Manufacturing Heavy or Large Structures like beams, trusses and pilings
- Manufacturing added value added support infrastructure and tools like custom wrenches
- Repairing capability for existing systems
- Manufacturing of locally integrated systems

---

**Surface Manufacturing with In Situ Resources Products To ISRU Elements**

- **Resource Transportation**
  - Surface mobility systems for Finished Product Utilization
  - Manufactured payload material handling

- **Product Storage & Distribution**
  - Parts for Life Support
  - Parts for Propulsion
  - Parts for Fuel Cells
  - Parts for Cooling Systems

- **Locally Integrated Energy Systems**
  - Silicon parts for Electronics, Photovoltaic Arrays
  - Fibreglass parts
  - Glass parts for PV arrays

- **Surface Construction**
  - Ceramics Components for Construction Materials Fabrication
  - Iron, Aluminium, and Steel Parts for Habitat Construction
  - Fibreglass parts for Composite Construction Materials, Concrete Substitute, Structural Components, Pressure Vessels (Habitats)
  - Parts from Slag for Habitat Radiation Protection
  - Slag Parts for Nuclear Reactor Shielding
Surface Mfg & Resources Interdependency with other ISRU Elements (13.4.4)

**ISRU Element Products To**

**Surface Mfg and Resources**

**Products From Surface Mfg & Resources**

**Locally Integrated Energy Systems**

**Resource Extraction**
- Regolith Excavation & Physical Beneficiation
- Regolith Volatiles Collection & Separation
- Surface Preparation

**Resource Transportation**
- Surface mobility systems platforms for Raw Resource Transportation
- Surface mobility systems for Finished Product Utilization

**Resource Processing**
- Raw materials for solar cell fab
- Raw materials for reflector/collector fab
- Raw materials for electronic parts fab
- Raw materials for thermal storage fav

**Product Storage & Distribution**
- Stored Gases/Liquids as inputs to Energy system fab

**Solar Collectors/Reflectors**

**Silicon Solar Cells**

**Power Beaming/Thermal Storage**

**Resource Extraction & Processing**
- Energy for Extraction
- Energy for Construction
- Energy for Processing

**Product Storage & Distribution**
- Energy for Life Support
- Energy for Propulsion
- Energy for charging for Fuel Cells
- Energy for Excavation
- Energy for Processing
- Energy for Construction

**Surface Construction**
- Energy for construction
- Energy for Excavation
- Energy for processing
### Key Assumptions:

- 2005
- 2010
- 2015

### Capability Roadmap 13: ISRU

#### Polar H₂ Mapping to 5 km
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated
- 0-g manufacturing & repair demonstrated

#### ISRU Resource Processing Roadmap (2005 to 16)

- **Polar ISRU**
  - Excavation & O₂ Utilization
  - Alm. Processing
  - Water/Soil Processing
- **Resource Utilizer**
- **Human Mission**
- **Major Event/Accomplishment/Milestone**
- **Solar Energy**
  - 4 days

### ISRU Science
- Lunar O₂ Pilot Plant Capability
- ISRU Robotic Hopper
- ISRU Science hopper capability

### 13.4.1 Additive Manufacturing
- ISS Repair Unit < 95% Reliability
- TRL6 Single Material Moon Unit
- TRL6 Combustion Synthesis Lunar Demo Unit
- TRL6 CVD Capability Demo
- TRL6 Fiberglass Lunar Unit
- TRL6 Multi-Material µ-g Mars unit

### 13.4.2 Subtractive Manufacturing
- TRL6 Lunar Milling Unit
- TRL6 Lunar CNC Unit
- TRL6 Lunar EDM Unit

### 13.4.3 Formative Manufacturing
- TRL6 Cold Forming Lunar Unit
- TRL6 Cold Forming Mars unit

### 13.4.4 Energy Systems
- Solar cell on glass > 5% Efficiency
- 5 Kg PV quality Si/metal from lunar regolith

### 13.4.5 Locally Integrated Systems
- TRL6 Dexterous Assembly Capability ISS Demonstration
- TRL6 Dexterous Assembly Capability for Lunar and Mars Probes
- TRL6 Dexterous Assembly Capability for Lunar and Mars Probes

### 13.4.6 Manufacturing Support Systems
Key Assumptions:

- Mars subscale human propellant production & storage capability
- ISRU science hopper capability
- Lunar O₂ Pilot Plant Capability
- Mars in-situ bio support capability
- Propellant, fuel cell, & life support production for Mars

13.4.1 Additive Manufacturing
- TRL6 Com. Syn. Mars Unit
- TRL6 Full scale Lunar & Mars MMF Units
- TRL6 Fiberglass Capability for Moon
- TRL6 Mars Surface CVD Unit
- TRL6 Fiberglass Capability for Mars

13.4.2 Subtractive Manufacturing
- TRL6 Full scale Mars Milling Unit
- TRL6 Full scale Mars CNC Unit
- TRL6 Mars EDM unit

13.4.3 Formative Manufacturing
- TRL6 Full scale Cold Forming Lunar Unit
- TRL6 Full scale Hot Forming Lunar Unit
- TRL6 Full Scale Cold Forming Mars Unit
- TRL6 Full Scale Hot Forming Mars Unit

13.4.4 Energy Systems
- Phobos In Situ Local Energy system

13.4.5 Locally Integrated Systems
- TRL7 Medium scale assembly and integration Units
- TRL8 Medium scale assembly and integration Units

13.4.6 Support Systems
- TRL6 Enhanced handheld NDE Capability
- TRL6 Final Integrated Mars NDE toolkit
- TRL6 Mars GPS System
Current State-of-the-Art for Surface Manufacturing with In Situ Resources

- Lunar Manufacturing with In Situ Resources has over a 30 Years History mostly paper studies that 90% manufacturing materials closure can be obtained from lunar materials.
  - However, the necessary technologies in additive, subtractive and formative manufacturing, integrated systems, and solar cell production have a very high terrestrial state-of-the-art.
  - Extensive microgravity materials processing experiments have been done in space in Apollo, Skylab, and Spacelab and include welding, metals solidification, vapor deposition, glass fiber pulling, and Lunar equivalent vacuum molecular beam epitaxy crystal growth in the Wake Shield orbital facility.

- Mars Manufacturing with In Situ Resources also is mostly paper studies but Mars surface science indicates that near 100% of manufacturing materials closure can be obtained from Mars and Phobos materials.
<table>
<thead>
<tr>
<th>Capability</th>
<th>Key Technologies or Sub-Capabilities</th>
<th>Capability Readiness Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>CRL</td>
</tr>
<tr>
<td>13.4.1 Additive Manufacturing</td>
<td>Solid Free-form Fabrication (SFF)</td>
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</tr>
<tr>
<td></td>
<td>Chemical Vapor Deposition (CVD)</td>
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<td></td>
<td>Fiberglass Fabrication</td>
<td>3</td>
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<tr>
<td></td>
<td>Combustion Synthesis</td>
<td>2</td>
</tr>
<tr>
<td>13.4.2 Subtractive Manufacturing</td>
<td>Milling</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CNC Lathe and CNC Turning</td>
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</tr>
<tr>
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<td>Electrical Discharge Machining (EDM)</td>
<td>2</td>
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<tr>
<td>13.4.3 Formative Manufacturing</td>
<td>Cold Forming</td>
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</tr>
<tr>
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<td>Hot Forming</td>
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<tr>
<td>13.4.4 Locally Integrated Energy Systems</td>
<td>Photovoltaic Cell/Array Production</td>
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<td>Solar Collector/Concentrator Production</td>
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<tr>
<td></td>
<td>Power Beaming Construction</td>
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<tr>
<td>13.4.5 Locally Integrated Systems &amp; Components</td>
<td>Precision Assembly</td>
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<tr>
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<td>Precision Joining/Fastening</td>
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<tr>
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<td>Metrology</td>
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<td>Capability</td>
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<tr>
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<td></td>
<td>Power Beaming Construction</td>
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<tr>
<td>13.4.5 Locally Integrated Systems &amp; Components</td>
<td>Precision Assembly</td>
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<tr>
<td></td>
<td>Precision Machining</td>
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<tr>
<td></td>
<td>Metrology</td>
<td>1</td>
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</tbody>
</table>
Summary of Surface Manufacturing Metrics For Technology Trades

- Rate of Production
- Power Consumed vs. Mass of Product Produced
- Mass of System vs. Mass of Product Produced
- Mean Time Between Failure
- Degree of System Autonomy
- Reagent Recycling Near or At 100%

Summary of Progress Metrics

- All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
- All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
- Continuous Operation for 30 days 5 years before need date.
- Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date
- Reduction of System Mass, for seed Manufacturing units.
- Although the systems will be human in-the-loop a maximum of autonomous and tele-operations must be developed.
- Systems require the development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment.
- Many of the Processes Involve Molten Materials, Designs to Handle this Molten Material Autonomously Are Not Trivial Exercises.
- Improved Energy Efficiencies.
- Understanding Of Reduced Gravity Effects On Processes.
- Mixed Gas Stream Separation.
- Significant Work Remains To Develop The Integrated Systems.
- Photovoltaic cell processes that utilize the lunar vacuum need to be improved to optimize the cell efficiencies.
- Interfaces must be developed between the extraction facilities and the production facilities.
- Methods must be developed for power management and distribution, metrology.
- Systems must be designed “up front” that are repairable by in situ processes.
Capability Development Strategy

- Early tests of in situ extraction of metals and silicon enable many in situ surface manufacturing and energy options.

- Early tests of fabrication and repair methods using these in situ materials enable the design of in situ maintainable systems for the Moon and beyond. These systems enable affordable safe, self-sustaining, space systems.

- Early demonstration of In Situ produced energy on the Moon will provide options for energy growth on the Moon and beyond that will cost less per energy unit as the system grows.

- Manufacturing and energy production on the Moon will enable lunar base growth at reduced cost and enable commercial development including the production of energy for use in space.

- Power beaming combined with in situ produced power will enable wireless transport of energy on the Moon and could be the basis for commercial Space Solar Power production.
ISRU Capability Element 13.5 Surface Construction

Kris Romig - NASA Chair
Dr. Eric Rice- External Chair
April 12, 2005
Surface Construction Capability Roadmap Team

Co-Chairs
- NASA: Kris Romig, NASA/JSC
- External: Dr. Eric Rice, ORBITEC

Government: NASA
- Rob Mueller, JPL/KSC
- Joseph Casas, MSFC

Government: Other
- Darryl Calkins, USACE Cold Regions Research & Engineering Lab

Industry
- Mike Fiske, Morgan Research Corporation
- Regina Pope, Qualis Corporation
- Trygve Magelssen, Futron Corporation
- Nancy Lindsey, Futron Corporation

Academia
- Dr. Leslie Gertsch, University of Missouri-Rolla
- Brad Blair, Colorado School of Mines
- Javier Diaz, Colorado School of Mines
- Begona Ruiz, Colorado School of Mines
- Paul van Susante, Colorado School of Mines
- Prof. Jeffrey Taylor, University of Hawaii

Other/Critical Volunteers
- Most of the above are volunteer contributors
- Broad ISRU industry & academic community (Space Resources Roundtable & STAIF Conferences)
Capability 13.5 Surface Construction

- Surface Construction is a capability that is necessary throughout the spiral development of NASA’s exploration vision
- Enabling for an extended human and robotic presence on any planetary surface
- Necessary for integration of surface assets

- Site Planning
- Surface & Subsurface Site Preparation
- Structure & Habitat Fabrication
- Radiation & Micro Meteoroid Debris Shielding
- Structure & Site Maintenance
- Landing and Launch Site Construction
Attributes 13.5 Surface Construction

- Site surveys and mapping
- Regolith construction material characterization
- Dust control and mitigation
- Moving of bulk regolith
- Grading of surfaces
- D-GPS like navigation capabilities
- Autonomous/telerobotic construction vehicles
Benefits of the 13.5 Surface Construction

- **Site Planning**
  - Site surveys & characterization of regolith for construction needs
  - Organization of emplaced and future surface assets

- **Surface & Subsurface Preparation**
  - Construction of science platforms (observatories)
  - Provides surface transportation infrastructures such as roads and landing/launch pads
  - Provides utility infrastructures for the site (utilidors)
  - Dust control and regolith stabilization
  - Increased accessibility to remote locations through transportation infrastructures

- **Structure & Habitat Fabrication**
  - Reduction of habitat mass launched from Earth

- **Bulk regolith shielding**
  - mitigates multiple threats simultaneously (radiation, thermal, debris)

- **Structure & Site Maintenance**
  - Maintainable and modifiable assets in place on lunar surface

- **Launch/Landing Pads**
  - Reduction of site degradation by flame and debris ejecta
  - Allows for closer proximity to current or future surface assets
  - Allows centralized location for propellant storage and refueling
13.5 Surface Construction

- Site Planning
  - Site Survey & Characterization
  - Architectural Layout & Master Planning
  - Civil Engineering Design
  - Geospatial Information System (GIS) Configuration Control
- Surface & Subsurface Preparation
  - Road Construction
  - Foundation Construction
  - Utilidor Construction
  - Terrain Shaping, Grading & Rock Clearing
- Structure & Habitat Fabrication
  - Construction Techniques & Methods
  - In Situ Building Materials
  - Access & Handling Equipment
  - In Situ Robotic / Human Construction
- Radiation & Micro Meteoroid Debris Shielding
  - Radiation Shelters
  - Shields for Nuclear Reactors
  - Micrometeoroid Shielding
- Structure & Site Maintenance
  - Integrity & Preventative Maintenance
  - Waste Management
  - Facility Management
- Landing & Launch Site
  - Landing/Launch Pads
  - Plume Debris Shielding
  - Exhaust Flame Management
  - Sheltered Propellant and Consumables Farms
  - Mars Lightning Protection
Surface Construction Interdependency with other Roadmaps

**Construction Products To Other Capabilities**

- Radiation shields for nuclear reactors
- Power Cable Deployment
- Power distribution layout

- Landing/Launch Pads
- Surface Support Infrastructure

- Shaping crater
- In-situ construction and fabrication
- Foundation design & preparation

- Landing pads/plume debris shielding
- Landing Site Characterization/Preparation

- Habitat/shelter fabrication
- Radiation shields from in-situ material
- Micro Meteoroid Debris Shielding

- Soil stabilization/dust control
- Roadway infrastructures
- Engineering properties of regolith

- Roadway infrastructures
- Construction End Effectors and attachments

- Geospatial Information System (GIS)
- Data fusion of regolith characteristics
- Engineering properties of regolith

**Capability Products To Construction**

- High-Energy Power & Propulsion

- In-Space Transportation

- Advanced Telescopes & Observatories

- Robotic Access to Planetary Surfaces

- Human Planetary Landing Systems

- Human Health and Support Systems

- Human Exploration Systems & Mobility

- Autonomous Systems & Robotics

- Scientific Instruments & Sensors

- Solar & nuclear power to support power-intensive ISRU activities

- ISRU-compatible propulsion
- Electromagnetic launch systems for delivery of ISRU products

- Resource location & characterization information
- Surface mobility system design & experience
- Pre-positioning & activation of ISRU assets

- Precision landing
- Delivery of ISRU capabilities to sites of exploration

- Crew/robotics/rovers to perform ISRU surface activities

- Robots/rovers to perform ISRU surface activities
- Software & FDIR logic for autonomous operation

- Instrumentation for resource location & characterization information
Surface Construction Interdependency with other ISRU Elements

**ISRU Element Products To**

<table>
<thead>
<tr>
<th>Resource Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ceramics for Construction Materials Fab (e.g. Bricks)</td>
</tr>
<tr>
<td>• Iron, Aluminum, and Steel for Structure &amp; Habitat Fabrication</td>
</tr>
<tr>
<td>• Fiberglass for Composite Construction Materials</td>
</tr>
<tr>
<td>• Slag for Bricks</td>
</tr>
<tr>
<td>• Slag for Habitat Radiation Protection</td>
</tr>
<tr>
<td>• Slag for Nuclear Reactor Shielding</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Regolith Excavation &amp; Physical Beneficiation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Surface mobility systems platforms for Raw Construction Resources</td>
</tr>
<tr>
<td>• Surface mobility systems for Finished Product Utilization</td>
</tr>
<tr>
<td>• Surface mobility systems for Resource Processing “Waste” removal.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface Manufacturing w/In-Situ Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Spare Parts for Surface Construction Systems</td>
</tr>
<tr>
<td>• Manufactured parts for Structure fabrication</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product Storage &amp; Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Stored Gases/Liquids as inputs to Surface Construction</td>
</tr>
</tbody>
</table>

**Surface Construction**

- **Site Planning**
- **Surface & Subsurface Preparation**
- **Structure & Habitat Fabrication**
- **Radiation & Micro Meteoroid Debris Shielding**
- **Structure & Site Maintenance**
- **Landing & Launch Site**

**Surface Construction Products From Surface Construction**

- **All**
  - General site planning and characterization
- **Resource Transportation**
  - Roadway infrastructure
  - Soil stabilization dust control
- **Product Storage & Distribution**
  - Utilidors / Cable deployment/ piping
  - Subsurface tank storage
  - Foundation/soil stabilization for tank farms
- **Resource Extraction**
  - Roadway infrastructure
  - End Effectors/ Attachments
  - Granular overburden
- **All**
  - Single and multifunctional structures
- **All**
  - Radiation shielding for crew/equipment
- **All**
  - General site & primary structure maintenance
- **Resource Transportation**
  - Landing & Launch site for off surface resource transportation
Additional Assumptions that the team used that drove the need for the capability:

- Lunar Base will be established at one location for staging to global Lunar access
- Early Lunar missions (4 – 90 Days) will require minimal Surface Construction (Landing/Launch, Protection, Site Planning)
- Later Lunar missions will be > 90 Days and evolve to commercial self sustainment with heavy emphasis on Surface Construction & permanent infrastructure
- Government provides base infrastructure for Science / Commercial customers (McMurdo/South Pole Analogy)
- Moon is a testbed and technology proving ground for Mars
- Mars missions will also have a primary Mars base with Infrastructure
Capability 13.5 Surface Construction Roadmap

Key Assumptions:

ISS

Moon

Polar ISRU

Resource

Solar Energy

Lunar Event Mars Event

Polar H₂ Mapping to 5 km
Ground Truth of Polar H₂ Source
Mars atmosphere propellant production & storage demonstrated

Subscale lunar regolith excavation & 
O₂ production & storage

Capability Roadmap 13: ISRU

13.5 Surface Construction

13.5.1 Site Planning

GIS

Architecture & Layout

Site Survey & Characterization

Civil Design

13.5.2 Surface & Subsurface Preparation

13.5.3 Structure & Habitat Fabrication

13.5.4 Radiation & Micro Meteoroid Debris Shielding

13.5.5 Structure & Site Maintenance

13.5.6 Landing & Launch Site

Lunar Event

Mars Event

2005

2010

2015
13.5 Surface Construction

13.5.1 Site Planning
- GIS
- Architecture & Layout
- Site Survey & Characterization
- Civil Design

13.5.2 Surface & Subsurface Preparation
- Utilidor Construction
- Road Construction
- Terrain Shaping, Grading
- Soil Stabilization
- Foundation Construction

13.5.3 Structure & Habitat Fabrication
- In Situ Structure Fab. Capability
- Micro Meteoroid Shielding
- Radiation Shielding (hab)
- Shielding

13.5.4 Radiation & Micro Meteoroid Debris Shielding
- Shields for Nuclear Reactors
- Micro Meteoroid Shielding
- Radiation Shielding (hab)
- Shielding

13.5.5 Structure & Site Maintenance
- Integrity & Preventative Maintenance
- Waste Management Facility Management

13.5.6 Landing & Launch Site
- Exhaust Flame Management
- Landing/Launch Pad
- Plume Debris Shielding
- Sheltered Propellant & Consumables

Key Assumptions:
- Mars subscale human propellant production & storage capability
- ISRU science hopper capability
- Lunar O₂ Pilot Plant Capability
- Regolith moving for construction & shielding
- Mars manufacturing & construction validated
- Propellant, fuel cell, & life support production for Mars
Current State-of-the-Art for Capability 13.5 Surface Construction

Team 13: In-Situ Resource Utilization

- **Site Planning**
  - Commercial Off the Shelf (COTS) GIS software available
  - Radar/Lidar automated mapping is available and proven (Shuttle/Mars/Venus)
  - Lunar / Mars Topography data sets are partially available
  - Some geophysical characterization is available (Apollo / Mars programs)
  - Lunar Regolith and properties available from Apollo program in the upper 2m, but lacking information at depth and at large spatial scales
  - Architecture & Civil engineering disciplines are mature for terrestrial applications

- **Surface & Subsurface Preparation**
  - Construction equipment (i.e., Bobcat, Caterpillar, Case, all-wheel steer loaders, excavators, work machines, backhoes, etc.)
    - terrestrial application @ TRL 9, Space @ TRL 1
  - Gravitometers, Transits, and Laser Surveying Equipment
    - terrestrial @ TRL9, Space @ TRL 1
  - GPS spatial control
    - terrestrial application @ SRL 9, Space @ TRL 1
  - Basaltic materials production TRL 1
  - Hand tools, concrete tools, screeds, power trowels, floats, etc.
    - terrestrial @ TRL9, Space @ TRL 2-9

- **Structure & Habitat Fabrication**
  - Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, including Commercial Off The Shelf (COTS) software
    - Water-based and waterless concretes
    - Sandbags
    - Blockmakers (compacted soil, carved rock, cast basalt)
    - Inflatable elements
    - Glass fiber and/or rods for concrete reinforcement or as structural elements
  - Lunar/Mars topography data sets are partially available
  - Some geophysical characterization is available (Apollo/Luna/Surveyor/Mars programs)
  - Lunar regolith and properties are available from the Apollo program

- **Radiation & Micro Meteoroid Debris Shielding**
  - Radiation, 25 rem/month (NASA’s current Limit) achieved with 13cm of regolith or 5m to stop GeV particles, Solar Events mitigated by ~50-100 centimeters of regolith.
  - Meteoroids, 45.9 cm of regolith (~34cm AL) protects against impacts of 7 cm (1.76 x 10\(^{-11}\) impacts/m\(^2\)/yr)
  - Thermal, tests have shown under a few centimeters of regolith (2-4 x 10\(^{-6}\) W/cm\(^2\)) or in a lava tube produces a nearly constant -35°C and -20°C
  - MMOD concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel) (TRL 9)
  - Lead free protective garments are commercially available (vests, suits, gloves, etc)

- **Structure & Site Maintenance**
  - In space maintenance and repair are evolving disciplines. New advances in self-healing materials to reduce maintenance, improve reliability and reduce risk are currently being tested at the University of Illinois. The self-healing capabilities of certain polymers have been demonstrated at the laboratory level.
  - EVA and IVA repairs are regularly performed on the International Space Station
  - Tile repair tools and materials are being developed as part of return to flight activities for the Space Shuttle

- **Landing & Launch Site**
  - Apollo style landings on the Moon showed ejecta occurred but did not threaten vehicle (23 metric Ton landed Mass)
  - Mars Viking, Pathfinder, MER missions show heritage but for small masses (1 metric Ton)
  - Huygens Probe landing on Titan
  - Extensive experience is available from Earth based spaceports.
  - Extensive experience with Earth based Propellant and consumables farms, but the mass, power, volume and reliability requirements are much more challenging for Moon/ Mars
  - JPL Skycrane type of devices may alleviate Landing/launch pad requirements
### Maturity Level – Capabilities for 13.5 Surface Construction

<table>
<thead>
<tr>
<th>Capability</th>
<th>Key Technologies or Sub Capability</th>
<th>Current CRL</th>
<th>Need Date</th>
<th>R&amp;D3</th>
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<tbody>
<tr>
<td><strong>Site Planning</strong></td>
<td>Site Survey &amp; Characterization</td>
<td>1</td>
<td>2014</td>
<td>II</td>
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<tr>
<td></td>
<td>Architectural Layout &amp; Master Planning</td>
<td>3</td>
<td>2010</td>
<td>I</td>
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<tr>
<td></td>
<td>Civil Engineering Design</td>
<td>1</td>
<td>2014</td>
<td>I</td>
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<tr>
<td></td>
<td>Geospatial Information System (GIS) Configuration Control Tool</td>
<td>3</td>
<td>2008</td>
<td>II</td>
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<tr>
<td><strong>Surface &amp; Subsurface Preparation (General)</strong></td>
<td>Road Construction</td>
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<td>2025</td>
<td>III</td>
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<tr>
<td></td>
<td>Foundation Construction</td>
<td>1</td>
<td>2025</td>
<td>II</td>
</tr>
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<td></td>
<td>Utilidor Construction</td>
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<td>2020</td>
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<tr>
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<td>Terrain Shaping, Grading &amp; Rock Clearing</td>
<td>1</td>
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<td>II</td>
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<td>Underground Structures</td>
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<td>III</td>
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<td>Soil Stabilization (Mars Dust)</td>
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<td><strong>Structure &amp; Habitat Fabrication</strong></td>
<td>Constructions Techniques and Methods (self deployable, inflatable, robotic, human)</td>
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<td>II</td>
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<td>In Situ Building Materials</td>
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<tr>
<td></td>
<td>Access &amp; Handling Equipment</td>
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<tr>
<td></td>
<td>In Situ Robotic / Human Construction Equipment</td>
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<tr>
<td><strong>Radiation &amp; Micro Meteoroid Debris Shielding</strong></td>
<td>Radiation Shelter (habitat, permanent)</td>
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<td>II</td>
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<td>Radiation Shields for Nuclear Reactors</td>
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<td>2020</td>
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<tr>
<td></td>
<td>Micro Meteoroid Shielding (habitat, permanent)</td>
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<td>2022</td>
<td>I</td>
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<tr>
<td><strong>Structure &amp; Site Maintenance</strong></td>
<td>Integrity &amp; Preventative Maintenance</td>
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<td>Waste Management</td>
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<td>Mars Lightning Protection</td>
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## Maturity Level – Technologies for 13.5 Surface Construction

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**Note:** TRL/SRL stands for Technology Readiness Level/System Readiness Level, R&D3 refers to Research and Development, and Need Date indicates the expected date for technology maturity.
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## Maturity Level – Technologies for 13.5 Surface Construction (3)

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## Maturity Level – Technologies for 13.5 Surface Construction (5)

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<td>&gt;15 cm</td>
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<tr>
<td>LGPS (Lunar GPS)</td>
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<td>Augers/Drilling/Piling</td>
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<td>Electrostatic Shield</td>
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Gaps for 13.5 Surface Construction

- Insufficient scale and resolution of topography for the Moon and Mars for detailed site planning
- Immature architecture and civil engineering disciplines for non-terrestrial surface applications
- Design & testing of construction equipment for & in the lunar environment
- Automation of construction processes
- High tensile-strength lunar based concrete
- Understanding of regolith properties (mechanical/physical) at probable landing sites
- Dust mitigation & techniques to control
- Surface materials capable of wear resistance
- Pre-manned surface construction requires complex robotics and teleoperations
- Shielding can only be used to protect a lunar station and its inhabitants from the effects of the thermal, radiation, and meteoroid mechanisms. Other methodology is needed to combat atmospheric, magnetic field, and gravitational field mechanisms effects
- The most significant challenge of using lunar regolith as a shielding material is that the regolith material is not ready to be installed immediately. This means that the habitat/crew is not fully protected immediately
- Regolith is not pre-processed for immediate installation; it must be excavated, lifted, dumped, and controlled which requires time, positioning and additional tools and machinery (automate to minimize crew time required) be designed, tested, and deployed
- Additional structural analyses/ issues and habitat accessibility for exterior maintenance issues will need to be addressed if the regolith shield/barrier is dumped directly on a habitat
- Self-healing capabilities of materials should also be tested in similar environmental conditions to assess performance (i.e. tested on the ISS)
- In situ production of spares and parts (a demonstration mission is needed to test this capability)
- Very little known about Mars lightning /electrostatics and Mars weather details
- No landing/Launch pad has been built on other planetary surfaces
ISRU Capability Element 13.6 Surface ISRU Product and Consumable Storage and Distribution

Co-Chairs:
Dr. Robert Zubrin, Pioneer Astronautics
Robert G. Johnson, NASA KSC

Presenter:
Robert Johnson
Surface ISRU Storage & Distribution Team

**Co-Chairs**

NASA: Robert G. Johnson, Kennedy Space Center  
External: Dr. Robert Zubrin, Pioneer Astronautics

**NASA**
- Rob Boyle  
- Renea Larock  
- David Plachta  
- Frederick Adams  
- Dr. Martha Williams  
- James Fesmire  
- Bill Notardonato  
- Brekke Scholtens  
- Eric Dirschka

**Industry**
- Rolf Baumgartner, TAI  
- Scott Willen, TAI  
- Larry Clark, Lockheed Martin  
- Ray Radebaugh, NIST
 Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

- Responsible for the efficient storage and distribution of all ISRU produced fluids and consumables to support mission success
  - Liquefaction of cryogenic products and maintenance of stores (LH2, LO2, LCH4, LN2, etc.)
  - Recycling and minimization of system losses
  - Storage of water (solid or liquid) and other earth storable fluids
  - Reagent storage for ISRU processes (if any)
  - Gas storage (buffer gasses and pneumatic uses)
  - Develop distribution options for wide variety of end users
    - Fixed service lines
    - Deployable service lines
    - Tanker trucks (in conjunction with ISRU transportation element)
    - Multi-use service station (rovers, astronauts, etc.)
    - Standardized user interfaces
  - Integrated thermal management of ISRU systems
Key attributes of Storage and Distribution Systems

- High storage capacity to launch mass and volume ratio
- Highly reliable systems (minimum repair and long service life)
- Highly redundant, modular, interchangeable active components
- Autonomous Control (minimum ground & flight crew involvement)
- Energy efficient systems
- Versatility - services many end users
- Expandable to support increasing mission scenarios/larger bases
- Robustness in harsh environment
- Increases inherent safety level of exploration architecture
Benefits of the Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

- Provides redundant cache of life support consumables (oxygen, buffer gasses and water)
  - Safe Haven stores for ASARA exploration architectures
- Provides long term, zero loss storage of earth return propellants
- Manages and delivers propellant/reagents for increased surface mobility
  - Rovers, hoppers, EVA suits and devices
- Increases mission reliability by pre-positioned stores of earth return propellant
  - Reduced launch mass from earth
  - Smaller exploration vehicles
- Enables energy storage for long lunar night
- Provides thermal storage capability to support integrated thermal management system
- Integral part of extraterrestrial recycling center (fuel cell water cycle)
- ISRU supported missions and precursors will require storage and distribution capability – near term technology needs
  - Long production times (to minimize size and mass of production plants) require storage capacity
- Highly reliable, autonomous systems are needed to minimize crew workload and maximize safety and mission success probabilities
- Launch volume and launch mass are key parameters to keep launch rate and size of launch vehicles at an affordable level
- Small, modular systems that can be easily expanded and/or replaced are highly desirable for long term exploration success
  - Common hardware and subsystems are to be used where ever possible
- Technology development for storage and distribution is synergistic with In-space Transportation Propellant Depots but unique environmental conditions warrant separate development and demonstration
- ISRU intermediate products (bricks, I-beams) are stored at production facility until end user is ready for delivery by ISRU transportation element
ISRU Storage & Distribution Interdependency with other Capabilities

**Products From Storage & Distribution**

- Fuel Cell Reactant Storage & Distribution
- Propellant Storage & Distribution
- Fluid storage and distribution for transfer to in-space depots
- Storage & Distribution of fuel cell reagents for rovers
- Propellant storage & distribution for surface hoppers or large sample return missions
- Propellant storage & distribution for lander reuse
- Gases for habitat inflation & buffer gases
- Life support consumable storage & distribution
- Gases for science equipment
- Propellants & fuel cell reactants for surface vehicles and aero-bots
- O$_2$ & water distribution for EVA
- Fluid storage & distribution

**Capability Products To Storage and Distribution**

- High-Energy Power & Propulsion
- In-Space Transportation
- Robotic Access to Planetary Surfaces
- Human Planetary Landing Systems
- Human Health and Support Systems
- Human Exploration Systems & Mobility
- Autonomous Systems & Robotics
- Scientific Instruments & Sensors

- Solar & nuclear power to support power-intensive ISRU activities
- ISRU-compatible propulsion
- Electromagnetic launch systems for delivery of ISRU products
- Interface coordination for fluid transfer
- Water by-products of rover fuel cells
- Interface Coordination for fluid transfer
- Delivery of ISRU capabilities to sites of exploration
- Interface coordination for fluid transfer
- Water by-products of rover fuel cells
- Robots/rovers to perform maintenance & repair
- Software & Failure Detection and Repair logic for autonomous operation
- Highly reliable, self-calibrating instrumentation and sensors
Storage and Distribution Interdependency with other ISRU Elements

ISRU Element Products To  ➔  Storage & Distribution  ➔  Products To ISRU Elements

Resource Extraction
• Raw or purified gases for storage

Resource Transportation
• Surface mobility for transporting tankers to end users
• Water by-products from rover fuel cells for recycling

Resource Processing
• All gaseous production for liquefaction and storage

Surface Manufacturing
• In-situ storage & distribution components

Surface Construction
• Initial deployment site prep
• Protection berm

Cryogenic Fluids

Chemical Reagents

Gases

Water/Earth Storable Fluids

Utility Connection & Interfaces

Hazard Detection & Suppression

Resource Extraction
• Fluids for extraction processes

Resource Transportation
• Fluids for transportation vehicles

Resource Processing
• Process fluid replenishment
• Water for reprocessing

Surface Manufacturing
• Fluids for manufacturing processes

Surface Construction
• Fluids for construction vehicles & equipment
Capability Team 13: ISRU Storage and Distribution Roadmap (2015 to 2035)

Key Assumptions:
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone

2015 2025 2035

13.6.1 Cryos
TRL7 TRL8 TRL9

13.6.2 Reagents

13.6.3 Gasses
TRL7 TRL8 TRL9

13.6.4 Water
TRL7 TRL8 TRL9

13.6.5 Connections
TRL7 TRL8 TRL9

13.6.6 Hazards
TRL7 TRL8 TRL9

Human-Scale Ground Demo of Cryo Consumable Station 365 Day
Current State of the Art
13.6 ISRU Product Storage & Distribution

Liquefaction:
- Flight rated cryo-coolers are limited in size and capacity
  - Larger prototype 80K (LOX) systems are at a much higher level than 20K (LH2) systems
    - 10W, 80K Cryocoolers at TRL9, 100W at TRL5, 500W at TRL 2
    - 10W, 20K Cryocoolers at TRL2

Storage:
- Flight rated fixed systems are mature but do not have integrated liquefaction systems
  - Vacuum jacketed, cryogenic tanks, supercritical tanks and high pressure gas storage are fixed volume, heavy systems (shuttle PRSD and centaur propellant tanks)
- Low initial volume tanks are at TRL 2

Distribution/Transfer:
- Automatic Umbilicals are TRL 4/5
- Deployable cryogenic transfer lines are at TRL 2

System Health:
- Autonomous control of dynamic processes is TRL 2
- Leak Detection systems in vacuum and low pressure atmospheres TRL 2/3
### Maturity Level – Capabilities for Storage and Distribution

<table>
<thead>
<tr>
<th>Capability</th>
<th>Key Technologies or Sub-Capabilities</th>
<th>Capability Readiness Assessment</th>
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## Capability Readiness Assessment

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</table>
Summary of Storage & Distribution Metrics For Technology Trades

- Mass of Commodity Stored/Launch Mass
- Volume of Commodity Stored/Launch Volume
- Thermal and Energy Efficiency of total system (input power/kg of propellant liquefied and stored/day)
- Mean Time Between Failure of active components
- Degree of System Autonomy (Ground controller manhours/week/kg of propellant stored)
- Propellant Transfer Losses (kg lost/kg transferred)
Summary of Progress Metrics (Same as Resource Processing)

- All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
- All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
- Continuous Operation for 30 days 5 years before need date.
- Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date.
Current Storage & Distribution Projects

Exploration Funded Projects

- Lockheed Martin has two Extramural Contract Awards
  - Integrated ISRU for Human Exploration - Propellant Production for the Moon and Beyond:
    - Liquefaction and storage of oxygen produced from lunar soil
    - Pulse tube cryocooler and lightweight, rigid tanks
  - High Energy Density Power System
    - High pressure gas storage for fuel cell reactants

- Several SBIR/STTR Phase II projects in recent years
  - Insulation systems
  - Cryocoolers
  - Valve technology
  - Automated umbilical
  - Gas detection sensors
Technology Gaps for Storage & Distribution

- 20K Cryocooler, space rated, 100’s of watts cooling
- Deployable tanks and distribution systems for cryogenic fluids
- Deployable tanks and distribution systems for high pressure gas.
- Long life compressors and motors for extraterrestrial applications
- Large Scale liquefaction and long term storage of cryogenics with flight weight systems/components
- Autonomous control of dynamic processes
- Leak detection in open vacuum or low atmospheric environments
- No calibration required - sensors and instrumentation
- Self-healing systems development
- Improved Energy Efficiencies/Integrated Thermal Management
There Is No One “Best Solution” For Storage and Distribution of fluids on the moon and Mars.

- One Technology May Trade Better Than Another Depending On The Architecture

As Architecture Options Mature Trade Studies Will Be Used To Down Select To A Set Of Technologies That Have The Potential Meet Mission Requirements.

These Technologies Will Be Developed To TRL 5 And Another Downselection Will Occur.

- Performance Metrics And Mission Requirements Will Be The Determining Factor.

The Suite Of Technologies Will be Flight Tested On Robotic Precursor Missions To Validate The Capabilities Readiness For Insertion Into The Critical Path For Human Missions.
ISRU Capability Element 13.7
ISRU Unique Test and Certification

Diane Linne and Michael Downey
NASA Co-Leads
Co-Chairs
NASA: Diane Linne
NASA: Michael Downey

NASA
- Phil Metzger
- Dr. Allen Wilkinson
- Robert Green
- Stan Starr
- ~15 NASA Facility Managers

Industry
- Larry Clark, Lockheed Martin Astronautics
- Dr. Laurent Sibille, BAE Systems

Academia
- Dr. Leslie Gertsch, University of Missouri-Rolla
- Brad Blair, Colorado School of Mines
Description of Capability 13.7: ISRU Unique Test and Certification

- Unique Test and Certification is the set of capabilities needed to support development, test, and certification of all of the ISRU technologies and capabilities

- Three Focus Areas
  - Modeling and Standards
    - extraterrestrial soil behavior and characterization models, ISRU component and system models
    - standardized procedures & guidelines for use of soil simulants, environmental testing, life/cycle tests, etc. for all elements
    - standardized set of metrics for modeling and technology comparisons
  - Simulants
    - Terrestrial geological materials (rocks, basalts, other minerals) selected for their similar characteristics to Lunar & Martian regolith, rock, and dust
    - Careful mixture of gases (and dust) to simulate Martian atmosphere
  - Unique Test Environments
    - Environmental simulation such as thermal extremes, low vacuum, thermal cycles, simulated atmosphere, dust, wind, radiation, surface and sub-surface conditions
    - Gravity simulation of micro-g, lunar & Martian gravity, low-g

- Unique Test and Certification receives unique or hardware-specific requirements definitions from the other six elements

- Unique Test and Certification provides to the other six elements the standard models, simulants, and environments required to design, develop, test and certify the ISRU hardware and systems
ISRU Unique Test & Certification Capabilities

In-Situ Resource Utilization

Modeling and Standards
13.7.1
- Modeling
  13.7.1.1
- Unique Environment Design/Test Standards
  13.7.1.2

Simulants
13.7.2
- Lunar Simulants
  13.7.2.1
- Martian Simulants
  13.7.2.2
- Other Bodies Simulants
  13.7.2.3

Unique Test Environments (normal gravity)
13.7.3
- Environmental Conditions
  13.7.3.1
- Planetary Surface & Sub-surface Conditions
  13.7.3.2

Reduced Gravity Test Environments
13.7.4
- Micro-Gravity
  13.7.4.1
- Lunar & Martian Gravity
  13.7.4.2
- Low Gravity
  13.7.4.3

Unique Test & Certification Capabilities
13.7
Attributes of Unique Test and Certification

- **Lunar regolith simulants**
  - Root simulants (basalts, anorthite, pyroclastic glass) - grain size distribution match, dust portion below 20 microns
  - Derivative simulants - additions to root simulants

- **Martian regolith simulants**
  - Spectral match to Martian regions (for remote sensing, in-situ optical analysis)
  - Extremely low moisture content, absence of organics, DNA
  - H$_2$O$_2$ modified TiO$_2$ (simulates available Martian atm. oxidant produced by UV)
  - Airborne dust portion is magnetic
  - Regolith grains are weathered, contain no toxic metals

- **Pressure and temperature environments**
  - lunar day: $10^{-10}$ torr / 255 - 390 K
  - lunar night: $10^{-11}$ torr / 120 K
  - lunar poles: $10^{-11}$ torr / 40 K
  - Mars: 2.5 - 7.5 torr / 145 - 240 K

- **Mars Wind:** 300 km/hr
Benefits of Unique Test and Certification

- **Modeling & Standards** - Enables apples-to-apples comparisons between technologies
  - Concurrent development and validation of ISRU soil, component, and system models will reduce Design, Develop, Test & Evaluation (DDT&E) time and costs
  - Final flight validation by testing alone may not be possible
  - Common set of standards provided to all elements guides technology and capability development

- **Simulants** - ensures tests conducted on physical (excavation, transport, etc.) & chemical processes are relevant (i.e. properly address key driving forces & processes)
  - Avoid depleting existing collections of lunar and meteorite samples
  - Provide large quantities of materials to test and validate designs
  - Provide a substitute in the absence of Mars samples
  - Available for validating other flight hardware such as landers, habitats, EVA equipment, etc.

- **Unique Test Environment**
  - Careful simulation of the actual operating environment significantly reduces the risk of implementing ISRU technologies
    - example when environment not properly simulated: Apollo lunar dust environment caused detriment to astronaut health in cabin, severe space suit degradation
    - example when environment successfully simulated: Space Shuttle APU developed at 1 atm, but when original design was tested with proper ascent profile hardware exploded – because test was performed hardware could be redesigned before flight program
  - Much cheaper to test in simulated conditions on/near Earth than flight demos on moon/Mars
  - Allows post-test access to hardware for analysis and modifications
Team Assumptions for Unique Test and Certification

- The need for physically & chemically-accurate lunar and Martian regolith simulants is a unique requirement for the development of the ISRU Capability
  - Other capabilities may be interested in dust simulants for final qual tests
  - Simulant materials will evolve in time based on new data provided by science missions to the moon and planets

- The need for highly-accurate test environments will be a strong early need for the development of the ISRU Capability
  - ISRU uses the environment, while most other capabilities fight it or merely “live” with it
  - ISRU capability developers will need to define & develop this capability even though other capabilities may then want to utilize it

- In general, the surface manufacturing, surface construction, and storage and distribution elements will be using material already partially beneficiated & processed by the other ISRU elements

- Test will need to be performed at the discreet gravity levels that represent the moon and Mars

- Single identified set of test and certification capabilities (models, simulants, facilities) for all ISRU elements provides consistency & reduces costs
Unique Test and Certification Interdependency with other Capabilities

Products from Unique Test/Cert

Unique Lunar and Mars test environment plus:
- Simulants for solar array development
- Long-term dust effects on ascent propulsion system operations
- Soil mechanics models for rocket plume cratering analysis
- Dust accumulation/removal on optics for surface telescopes
- Soil mechanics for tire/soil interaction
- Long-term dust effects on spacesuits, life support systems, etc.
- Opportunity to piggy-back on tests in unique environments

Products to Unique Test/Cert

- Compact power for surface demos
- In-space transportation
- Advanced telescopes and observatories
- Robotic access to planetary surfaces
- Human Health and Support Systems
- Human Exploration Systems & Mobility
- Autonomous Systems & Robotics
- Scientific Instruments & Sensors
- Advanced modeling, simulation, analysis

- Advanced sensors and instruments for tests
- Advanced sensors and instruments for robotic in-situ measurements
- Computational software technologies to support development of ISRU models
- Infrastructure libraries and tools for science/engineering modeling
Unique Test and Certification Interdependency with other ISRU Elements

ISRU Element Products To

Unique Test and Certification

Products or Services From Unique Test and Certification

Modeling and Standards

Simulants

Unique Test Environments - Normal Gravity

Reduced Gravity Test Environments

Resource Extraction
- All simulant types
- Stratigraphy (layering simulation)
- Test and certification environment

Material Handling and Transport
- All simulant types
- Test and certification environment

Resource Processing
- All simulant types
- Test and certification environment

Surface Construction
- Regolith and dust simulants
- Test and certification environment

Surface Manufacturing w/ In-Situ
- Dust simulants
- Test and certification environment

Product Storage & Distribution
- Dust simulants
- Test and certification environment

All Elements
- Unique or hardware-specific requirements definition
- Mission-driven requirements definition (e.g. length of time for tests)
13.7.1 Modeling and Standards

13.7.2 Simulants
- Lunar Regolith
- Lunar rock
- Lunar dust
- Mars Regolith
- Mars rock
- Mars atmos/dust

13.7.3 Unique Test Environments (normal gravity)

13.7.4 Reduced Gravity Test Environments
Capability Team 13: In Situ Resource Utilization (ISRU) Unique Test and Certification Roadmap (2015 to 35)

Key Assumptions:
- Robotic or Predeployed ISRU mission
- Human Mission
- Major Event/Accomplishment/Milestone
- ISS
- Moon
- Mars

Capability Roadmap 13: ISRU
- Polar H₂ Mapping to 5 km
- Ground Truth of Polar H₂ Source
- Mars atmosphere propellant production & storage demonstrated
- 0-g manufacturing & repair demonstrated
- Subscale lunar regolith excavation & H₂O extraction
- Validation of silicon/metal extraction from lunar regolith
- Subscale Mars regolith excavation & H₂O extraction
- Validation of in-situ solar electricity production
- Total lunar O₂ Pilot Plant Capability (30-60 KWe)
- ISRU Robotic Hopper
- Lunar O₂ Pilot Plant Capability (1-2 KWe)

13.7.1 Modeling and Standards

13.7.2 Simulants

13.7.3 Unique Test Environments

13.7.4 Reduced Gravity Test Environments
### Modeling and Standards

- **Regolith Characterization and behavior**
  - extensive literature on modeling terrestrial soil mechanics
  - powder industry has elaborate bench-top to full process plant development process - extremely expensive and time-consuming process
  - Granular flow clogging is a common industrial problem with ‘kick-the-chute’ solutions
- **Component models of various fidelity developed by individual researchers to support very specific short-term studies and goals**
  - primarily for chemical processing and storage components
- **System models**
  - ISRU economic model in development by Colorado School of Mines - requires technical inputs for components
- **Design/Test Standards**
  - ASTM and ASAE standards for (terrestrial) traction and soil mechanics

### Simulants

- ~27,000 lbm of JSC-1 lunar simulant produced in early 1993 - no longer available
  - represents an average chemical composition between the highlands and mare regions of the moon
- **MLS1 lunar simulant (1987) - no longer available**
- **FJS1 - lunar simulant - Japan - available in modest quantities**
- **JSC Mars1 Martian simulant chosen for reflectance spectrum close to Mars bright areas**
- **Atacama Desert Martian simulant chosen for very low organic concentrations**
Current State-of-the-Art for Unique Test and Certification

- **Lunar Test Environments**
  - Complete thermal range available
  - Large chambers can reach $10^{-8}$ torr at best
  - Current best chambers identified so far offer mix of requirements, sizes, and capabilities
    - Largest at best pressure and temp ($10^{-8}$ torr and 40 K (or other lunar temps)) is 4 m diameter (K-Site at NASA GRC-Plum Brook) - *but not currently rated for simulants (oil diffusion pumps)*
    - Largest at best pressure and temp ($5 \times 10^{-7}$ torr and 80 K) that can tolerate simulants (cryopumps) is 7.5 m dia x 20 m (VF6 at NASA GRC) - *cannot control to other temps and has not actually tested with simulants*
    - Largest at best pressure and temp ($10^{-6}$ torr and 80 K) that has used simulants and can vary/control temperature (Space Power Facility at NASA GRC - Plum Brook)
    - Largest at best pressure, temp ($10^{-6}$ torr and 77 K) that has used simulants with remote manipulation capability is 2 m x 2 m x 3 m (Planetary Surface Environment Simulation facility at Lockheed-Martin)

- **Mars Test Environments**
  - Atmospheric gases have been simulated
    - JSC Mars Simulation Chamber (e.g.), 6.1 m diameter
    - typically 3-gas simulation (CO$_2$, Ar, N$_2$), but some have added O$_2$ and H$_2$O
  - JSC .6 m belljar simulation of atmosphere, wind, and Martian dust
  - Mars Wind Tunnel (NASA Ames) simulates winds/dust to 100 m/s, 1.2 m square by 16 m long - no thermal simulation

- **Micro/partial gravity for short durations**
  - Drop towers: 5.2 sec max for micro-g only, 1 m dia x 1.65 m high
  - Reduced-gravity aircraft: 20 sec micro-g, 30 sec lunar-g, 40 sec Martian-g, 50' x 8' x 6.5' test hardware
  - Sounding rockets (5 - 6 mins, 1/2 m x 2 m test hardware)

- **Micro-g for long durations**
  - ISS glove-box (.9m x .5m x .4m (ave))
  - ISS integrated experiment racks (delivered to Station in May, 2007)
    - Combustion Integrated Rack: 0.4 m dia x 0.6 m; Fluids Integrated Rack: 1.1 m x .9 m x .5 m
## Maturity Level – Capabilities for Unique Test and Certification

### Modeling and Standards

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<thead>
<tr>
<th>Capability</th>
<th>Key Technologies or Sub-Capabilities</th>
<th>Capability Readiness Assessment</th>
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<td>Regolith characterization and behavior - granular flows</td>
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### Simulants

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<td>(10^{-10}) Torr/255 - 390 K</td>
<td>(5 \times 10^{-8}) torr/ meets temp. requirement</td>
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<td>Lunar Night</td>
<td>(10^{-11}) Torr/120 K</td>
<td>(5 \times 10^{-8}) torr / meets temp. requirement</td>
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<td>Lunar Poles</td>
<td>(10^{-11}) Torr/40 K</td>
<td>(5 \times 10^{-8}) torr / meets temp. requirement</td>
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<td>Mars (varies by day/night and winter/summer)</td>
<td>(300 - 1000) Pa (0.044 - 0.145 psi)/145 - 240 K</td>
<td>several facilities meet pressure and temperature</td>
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<tr>
<td>Mars Winds</td>
<td>300 km/hr (190 mph)</td>
<td>Meets wind, pressure, and simulants but not temp.</td>
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<td>Ability to accept simulants</td>
<td>dust (&lt;20 microns) regolith (&gt;20 microns)</td>
<td>demonstrated in 10-6 torr facility; possible in 10-7 torr facilities</td>
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<td>Reduced Gravity (specify g-level and max. time per test)</td>
<td>micro-g 1/6th Earth-g (moon) 0.38 Earth-g (Mars)</td>
<td>yes - long duration 30 seconds max 40 seconds max</td>
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<td>Root Simulant: Basalt-rich material representing Mare (lowlands) locations</td>
<td>Lunar regolith simulants</td>
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Technology Gaps for Unique Test and Certification

- **Models and Standards**
  - Detailed knowledge of the Martian regolith composition, fabric, microstructure
  - Role of tribo-charging and electrostatics
  - Ice composition and mechanics included in soil models
  - Basic physics of granular flows (static and dynamic equation equivalence of Navier-Stokes for fluids)
  - Traction, soil shear, granular mixing and separation issues in reduced gravity
  - Models that allow parametric sub-components performance inputs to identify effect on total component performance
  - End-to-end system models
  - Test protocols for use of simulants in component and system testing

- **Simulants**
  - Small fractions below 5 microns to adequately represent lunar dust
  - Anorthite mineral to represent ‘highlands’ regions (including polar regions)
  - Agglutinate fractions (represents up to 40% of typical lunar regolith mass)
  - Lunar rocks
  - Martian simulants for magnetic portion, rocks, <100 microns, chemical signature

- **Unique Test Environments**
  - Large chambers with vacuum levels below $10^{-8}$ torr (down to $10^{-11}$ torr - need actual requirement)
  - Vacuum chambers tolerant of simulants on large scale
  - Remote equipment to handle, distribute, charge, etc. simulants within vacuum chamber

- **Reduced Gravity Test Environments**
  - Capability for long-term simulation of reduced gravity (e.g. lunar or martian-g) – currently must send robotic demos to learn about and prove out reduced gravity capability
Unique Test and Certification Capability Development Strategy

- **Modeling and Standards**
  - Develop models with best existing data to aid in near-term trades
  - Structure initial models to allow continual updates of additional capability/technology definition as performance data becomes available
  - Develop standards for metrics across all ISRU elements

- **Simulants**
  - Develop root simulants for basalt-rich lowlands, anorthite and feldspathic basalt highlands, pyroclastic glass
  - Develop derivative simulants from mixture of roots to reflect mineralogical diversity of specific locations
  - Develop dust material simulants
  - Develop materials specific to lunar poles (ice and elemental concentrations)
  - Continually update simulant composition as additional information from science missions becomes available

- **Designate some vacuum chambers as “dirty” facilities, others as “clean” facilities**
  - Once dust and regolith simulants are introduced, may be difficult to clean back to level required for other Capability development (e.g. Adv Telescopes and Observatories)

- **Tap into expertise in HSR&T (former microgravity) community to evaluate which technologies and processes from each element will be gravity-dependent**
  - Determine whether micro-gravity will be sufficient/appropriate or whether actual gravity-level simulation is required
### Modeling and Standards

- **Regolith characterization and behavior**
  - predict standard soil mechanics indices ±10% (cone penetration, vane torsion, etc.)
  - Predict excavator torque and specific energy requirements ±10%
  - Predict vibration response of designed hardware in terrestrial environment ±10%
  - Predict flow rate, jamming power spectrum, energy spectrum required for unjamming ±20%
  - compared to terrestrial hardware tests

- **Component and System models**
  - Model matches existing hardware to ±5% on mass, power, useful output, recycling/resupply of consumables
  - Model successfully run by new user(s) with identical results
  - Number of components/capabilities included in system model

### Simulants

- Validation of simulants by comparison to actual lunar samples or in-situ Martian measurements
- Quality control process for simulant material to ensure batch-to-batch homogeneity

### Unique Test Environments

- Vacuum and thermal matching
- Tolerance to dirt (and willingness)
- Size
- Cost
- Duration of reduced-gravity environment
ISRU For All Government (NASA, DOD, DOE, NOAA, Science) & Commercial Applications

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Brad Blair, Colorado School of Mines, bblair@mines.edu
Mark Nall, Klaus Heiss, Woody Anderson, Peter Curreri, Eric Rice, Ed McCullough, Mike Duke
Fundamental Purpose For Commercializing ISRU

  - Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests

- NASA Strategic Objective 17 (from NASA Strategic Plan, 2005)
  - Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit

- NASA Strategic Objective 18 (from NASA Strategic Plan, 2005)
  - Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve or increase the involvement of the U.S. private sector in design and development of space systems

- Unless the cost for Earth launch, in-space transportation, and planetary surface infrastructure and operations steadily decreases over time, ‘sustained’ and simultaneous human Moon and Mars operations will not be possible
  - Commercialization of government-developed technology and lunar infrastructure offers a rational pathway to sustainable exploration
Benefits of Commercializing ISRU

- Government-developed and operated ISRU can reduce cost and risk of human exploration compared to non-ISRU architectures, however further reductions in costs to government are possible if ISRU is ‘commercialized’

- Money saved due to commercial ISRU and resulting infrastructure can support other aspects of the Space Exploration Program
  - Lunar ISRU commercialization can become a hand-off strategy, enabling human Mars exploration

- A partnership between industry and NASA can benefit both parties
  - NASA Benefits
    - Reduced operation costs and ‘sustained’ human exploration
    - Access to extensive terrestrial hardware and experience
    - Industry could steer technology development toward near-term market applications
    - Non-aerospace industries could provide additional congressional support
  
  - Industry Benefits
    - Anchor tenant and co-funding for technology and operations into emerging markets
    - Demos and ground/space laboratories to prove concepts and reduce risk for business plans and financing
    - Government support for favorable regulation
    - Reduced development costs and increase the likelihood of spin-off products and services
Lunar Commercialization Could Enable Budget for Mars

**Infusion of Private Capital into Lunar Base**
- Commercial developers acquire NASA infrastructure
- Lunar base *no longer requires NASA funding*
- Mars exploration benefits include commercial propellants

**Commercialization of Lunar Base**
- Lunar facility continues expansion
- Infrastructure is operated by industry
- ISRU further reduces Mars exploration cost

**Transition to Human Mars Exploration**
- Transfer lunar facility to private consortium
- Costs of lunar base assumed by industry
- ISRU enabled commercial activities

**Human Lunar Exploration**
- Begin construction of Lunar Base
- ISRU enabled exploration
- ISRU commercialization precursors

- **Red Line** shows projected NASA budget limit (assuming 2% annual inflation)
- **Gold Line** shows how early commercial engagement could increase total funding profile

**Lunar Commercial Activity Expands to Earth Orbital Markets**
- Note: Green block signifies private capital investment in lunar infrastructure, not NASA funding
To ‘commercialize’ ISRU, markets besides NASA human exploration are required.

Note: Commercialization is **NOT** engaging a private company to design/build something where their main source of profit comes from the process and not the final product’s use.

- Identify ISRU capabilities that could be of benefit to multiple customers (Science, National Security, Public Interest, Economic Security)
- Identify impediments to commercialization (technology, policy/regulations, risk, etc.)
- Initiate NASA/Government activities to promote ISRU commercialization
  - Infrastructure, research & development, coordination, etc.
- The ‘Business Model’ will drive the Missions; Early Human exploration ISRU demonstrations could:
  - Develop and demonstrate technologies & operations to reduce risk
  - Business models can accelerate/defer ISRU demo prioritization and timing

Traditional NASA Approach (Begin with Exploration goals)

- Define Exploration Requirements
- Identify Needed Capability
- Identify & Select Technologies
- Perform System Demonstrations
- Incorporate into Human Mission Architecture
- Attempt to Commercialize System

Business Model Approach (Begin with Market goals)

- Identify Market & Needed Capability
- Define Initial Capital-Cost Constraints
- Identify & Select Technologies*
- Determine Commercial Feasibility
- Initiate Commercial Activity w/ System Demo
- Attempt to Satisfy Market
- Incorporate into Human Mission Architecture

*Selection of Technology is based on optimum cost not performance
Market Identification

- Most Space Resources-related Exploration Applications have Commercial Potential
  - Propellants, consumables, power system elements, building materials, fabricated parts and higher-order manufactured items

- Possible Market Areas for commercialized space ISRU in next 10 to 15 years
  - Science (NASA): lunar-based astronomical observatories
  - National Security (DOD, DOE):
    - Earth and space surveillance
    - Satellite refueling, space control, debris management
    - Eliminate dependence on foreign energy (power beaming, Helium-3, etc.)
    - Eliminate dependence on foreign strategic metals (NEOs)
  - Public Interest (NOAA): weather monitoring, Earth monitoring
  - Economy:
    - Space Commercial: communications & data, power, transportation, tourism/habitats
    - Earth Applications: mining, petrochemical, power, construction, powder, manufacturing
Near & Far Term Space Commercial Applications

- **Remote Sensing**
  - Earth viewing
  - Astronomical observatories

- **Self-Sustaining Colonies**
  - Tourism
  - Resort construction & servicing

- **Power Generation**
  - Power beaming from lunar surface
  - Helium-3

- **Cis-Lunar Transportation & Propellant**
  At Earth-Moon L1 for following:
  - NASA Science & Human Exploration Missions
  - Debris Management
  - Military Space Control (servicing; moving, etc.)
  - Commercial Satellite Delivery from LEO, Servicing, & Refueling
  - Delivery of resources/products for Space Solar Power
Commercial Lunar Propellant Production Example

**Team 13: In-Situ Resource Utilization**

- Begin with projected Human Exploration requirements
  - Initial market: Propellant for Direct-return from Moon to Earth
  - Evaluate other markets and growth in production rate and infrastructure to enable propellant depot at Earth-Moon (EM) L1 for increased human exploration & other markets (i.e. LEO to GEO satellite transfer & DOD satellite refueling)
- Perform commercial propellant feasibility assessment based on Initial & long-term markets
  - Utilize NASA human lunar missions and ISRU-compatible transportation elements as ‘anchor’ for initial infrastructure on Moon
  - Evaluate growth in infrastructure and production required for E-M L1 propellant depot
- Select ISRU technologies & processes and propellant storage & transportation concepts based on projected demand and growth to obtain fastest return on investment
- Utilize NASA ISRU demonstration missions to reduce risk for complete commercial venture and provide initial capability

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**Case Study: FY02 CSM/NExT Report on Commercial Feasibility Assessment of Lunar Propellant Production**
Commercial Lunar Propellant Feasibility Study

Project Description

- FY02 Study Funding provided by the NASA Exploration Team (NExT)
- Scope: Examine the **commercial feasibility** of lunar-based transportation fuel production and delivery
- Participants: JPL / CSM / CSP Associates, Inc.

Assumptions

- Water is produced on the Moon, along with the propellant needed to transport it to L-1 and LEO
- Only **commercial infrastructure** is assumed (this study pre-dates the NASA Exploration Vision and does not consider human exploration)
- Commercial infrastructure is deployed on lunar surface (ISRU plant), at L1 (fuel depot) and in LEO (fuel depot)
- Hardware replacement at 10%/yr
- Launch Costs: $90M/ton Moon, $35M/ton GEO, $10M/ton LEO

Model Feasibility Conditions

Zero non-recurring costs (DDT&E)
30% Production cost reduction
2% Ice concentration
2x Demand level (i.e., 300T/yr)
25% Price Increase
Space Commercial Development Which Leverages Human Exploration Architecture

“Fort to City” Approach

- **Phase 1: Provide products/services to “Fort”: NASA Lunar surface human exploration**
  - Propellant production for lunar ascent: oxygen, fuel
  - Consumables for life support: oxygen, nitrogen, water
  - Power system growth: fuel cell consumables, solar energy (electric/thermal)
  - Site preparation & construction: berms, radiation shielding

- **Phase 2: Provide products/services to “Traders/Prospectors”: Other government & Earth-focused commercial activities**
  - Power generation: helium-3, power beaming to Earth, space solar power
  - Transportation:
    - Propellant production and delivery to Earth-Moon L1 for cis-lunar transportation, satellite servicing, and space control
    - Propellant & consumable production for surface transportation and hoppers
  - Surveillance: weather, ‘enemies’, surface & space astronomical and Earth observatories

- **Phase 3: Provide products/services to “Farmers”: Surface industry and tourists**
  - Surface power generation growth
  - Infrastructure Growth: habitats/shelters, roads, life support consumables
Path to Commercialization

- **Initiate NASA-Government Tasks to Enable Space Commercialization**
  - Demonstrations to validate concepts & build business case
  - Regulation reforms: tax incentives, property rights, liability, ITAR / export control

- **Utilize Multiple Methods for ‘Commercializing’ ISRU**
  - Traditional development BAA/Contracts
  - NASA Innovative Partnership Program (IPP)
  - Contract for ‘services’
  - Government-Industry Consortiums (Comsat or Galileo)
  - Government-Industry “Infrastructure” Partnerships (railroad, air-mail, highways, etc.)
  - Prizes
  - Creation of Earth, LEO, and Lunar-based ISRU test & development laboratories

- **Establish a committee of representatives from NASA, industry, and academia**
  - Define the roles that NASA and Industry will have as space exploration matures.
  - Promote enactment of regulations and policy that enable short and long-term lunar commercialization goals
  - Initiate and establish policies, procedures and incentives to turn over Lunar infrastructure assets to industry so NASA can focus on exploring beyond the Moon.
  - Prioritize technology development & demonstrations which best meet goals of both reduced costs to NASA human exploration & space commercialization
  - Define scope and charter for Government-Industry Space Consortiums

➢ **Early engagement of NASA/commercial partnerships is required to maximize commercial benefits**
ISRU Commercialization Challenges

- **Financing**
  - Government funding for space is fairly flat
  - European Galileo project demonstrates industry-banks willing to invest when government is anchor tenant
  - Iridium, Space-X, Virgin Galactic, & Bigelow efforts demonstrate investment funding for commercial space activities are possible
  - Economic & market research can provide early feedback on commercial feasibility

- **Regulations & Policy**
  - International Agreements (Outer Space Treaty, Moon Treaty)
  - US Laws (Tax incentives, property rights, liability, ITAR / export control, etc.)
  - NASA policies, procurement and Industry cooperation infrastructure

- **Technical**
  - Level of maintenance & repair unknown
  - Uncertainty in resources
  - Uncertainty in performance and amount regolith excavation required
  - Sealing for regolith processing systems

- **NASA as ‘anchor tenant’** can be catalyst, coordinator, and ‘glue’ to make commercialization of ISRU and space possible
## Implementing ISRU Commercialization

### Commercial Partnership Matrix

<table>
<thead>
<tr>
<th>Activity</th>
<th>Outcome</th>
<th>Benefits to NASA/USG</th>
<th>Time Frame</th>
<th>Process</th>
<th>Key Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Partnerships for multi-use technology development</strong></td>
<td>Leveraging off industrial development has demonstrated enormous savings to NASA</td>
<td>Reduced cost to develop ISRU technology and immediate public benefit from exploration</td>
<td>Currently in existence</td>
<td>NASA ISRU focused partnerships through the Research Partnership Centers</td>
<td>Continued need to leverage funding and maintain political support</td>
</tr>
<tr>
<td><strong>Involvement of potential industrial developers in ISRU planning</strong></td>
<td>Greater chance of successfully privatizing NASA’s Lunar infrastructure</td>
<td>Lunar ISRU assets available for NASA use while freeing up funding for going to Mars</td>
<td>ASAP Since this can influence Lunar exploration architecture planning</td>
<td>Establishment of an industry working group to advise on architecture planning</td>
<td>Exploration beyond the Moon remains a priority for NASA</td>
</tr>
<tr>
<td><strong>Prizes for ISRU development</strong></td>
<td>ISRU system level demonstrations and potentially Lunar robotic ISRU demonstrations</td>
<td>Reduced cost of demonstrating ISRU technologies since NASA only pays for winners</td>
<td>ASAP for terrestrial demonstrations</td>
<td>Centennial Challenge announcement</td>
<td>Some ISRU is deemed beneficial to exploration</td>
</tr>
<tr>
<td><strong>Establish a Comsat / Intelsat Type Federal Government Corporation (FGC)</strong></td>
<td>Create organization that can sponsor research, coordinate ISRU efforts, and enter into long term, binding agreements with industry and other government organizations with more flexibility than NASA can</td>
<td>More efficient industrial ISRU development process that allows NASA to focus on exploration</td>
<td>ASAP (2007)</td>
<td>White House / ESMD works with Congress to establish a FDC for space resource development</td>
<td>Political support for this approach exists or can be created</td>
</tr>
<tr>
<td><strong>Anchor tenancy agreements for future purchase of In-Situ Resources</strong></td>
<td>Non-NASA / Government investment in ISRU production</td>
<td>Reduced cost to utilize In-Situ Resources and enhanced commercial space infrastructure</td>
<td>As soon as Lunar exploration architecture (ISRU requirements) is finalized</td>
<td>RFP for projected quantities of energy, gases, etc., needed for exploration</td>
<td>Significant In-Situ Resources are needed to support exploration</td>
</tr>
<tr>
<td><strong>Homesteading &amp; Property Rights</strong></td>
<td>Enables independent commercial, market driven activities related to space exploration and development</td>
<td>Allows NASA exit strategy from Operations, enables Exploration focus</td>
<td>2007 - Jamestown Anniversary</td>
<td>Implement and expand the NASA 1958 Act</td>
<td>Progressive emergence of future market opportunities</td>
</tr>
</tbody>
</table>

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Team 13: In-Situ Resource Utilization

Gerald B. Sanders/JSC, gerald.b.sanders@nasa.gov

April 12, 2005

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ISRU Capability Team Wrap-up
ISRU Challenges

Maximize benefit of using resources, in the shortest amount of time, while minimizing crew involvement and Earth delivered infrastructure

- **Operation in severe environments**
  - Operation and interaction with dust (fine particles are invasive and highly abrasive)
  - Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Methods to mitigate dust/filtration for Mars atmospheric processing

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery (No crew for maintenance; Non-continuous monitoring)
  - Long-duration operation (ex. 300 to 500 days on Mars surface for propellant production)

- **High reliability and minimum (zero) maintenance**
  - High reliability due to no (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Development of highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Development of highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)
ISRU Challenges (Cont.)

- Early mass, cost, and/or risk reduction benefits
  - Methods for energy efficient extracting oxygen and other consumables from lunar or Mars regolith
  - Methods for mass, power, and volume efficient delivery and storage of hydrogen
  - Processing and manufacturing techniques capable of producing 100’s to 1000’s their own mass of product in their useful lifetimes, with reasonable quality.
  - Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - In-situ manufacture of spare parts and equipment with the minimum of required equipment and crew training
### ISRU Crosswalk of CRM Relationships

<table>
<thead>
<tr>
<th>Team 13: In-Situ Resource Utilization</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1. High-energy power and propulsion</td>
<td><strong>Critical Relationship</strong></td>
<td><strong>Moderate Relationship</strong></td>
<td><strong>No Relationship</strong></td>
<td><strong>Same element</strong></td>
<td><strong>Same element</strong></td>
<td><strong>Same element</strong></td>
<td><strong>Same element</strong></td>
<td><strong>Same element</strong></td>
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<td><strong>Same element</strong></td>
</tr>
</tbody>
</table>

**Critical Relationship (dependent, synergistic, or enabling)**

**Moderate Relationship (enhancing, limited impact, or limited synergy)**

**No Relationship**
## Examples of CRM Relationships

### 2. In-space transportation

<table>
<thead>
<tr>
<th>Capability Flow &amp; Criticality</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Processing, storage and Distribution</td>
<td>Propellant made on Moon/Mars may provide significant mass savings</td>
</tr>
</tbody>
</table>

### Earth Departure Stage

<table>
<thead>
<tr>
<th>Capability Flow &amp; Criticality</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Processing, storage and Distribution</td>
<td>Propellant made on Moon may be used for Earth (L1) Departure Stage</td>
</tr>
</tbody>
</table>

### Earth Return Stage

<table>
<thead>
<tr>
<th>Capability Flow &amp; Criticality</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Processing, storage and Distribution</td>
<td>Propellant made on Mars may be used for Earth Return Stage</td>
</tr>
</tbody>
</table>

### 8. Human exploration systems and mobility

<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Mobility - Surface Mobility Systems</td>
<td>Geologists will require mobility to access resource areas for evaluation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refueling and fluids support systems</td>
<td>Automated umbilicals will supply breathing air, propellants and purges</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Topic or Subsidiary Capability</th>
<th>Nature of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell</td>
<td>In Situ Produced Propellants can supply fuel cells for surface mobility</td>
</tr>
</tbody>
</table>
## ISRU Interaction w/ Strategic Roadmap Activities

<table>
<thead>
<tr>
<th>SR-#</th>
<th>Short</th>
<th>Full Name</th>
<th>Chartered Objective</th>
<th>In Situ Resource Utilization (ISRU)</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Moon</td>
<td>Robotic and Human Lunar Exploration</td>
<td>Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.</td>
<td>ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection</td>
<td>ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection</td>
</tr>
<tr>
<td>2</td>
<td>Mars</td>
<td>Robotic and Human Exploration of Mars</td>
<td>Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future</td>
<td>ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection</td>
<td>ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection</td>
</tr>
<tr>
<td>3</td>
<td>Solar System</td>
<td>Solar System Exploration</td>
<td>Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.</td>
<td>Search for Solar System Resources</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>4</td>
<td>Earth-like Planets</td>
<td>Search for Earth-Like Planets</td>
<td>Search for Earth-like planets and habitable environments around other stars using advanced telescopes.</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>5</td>
<td>CEV / Constellation</td>
<td>Exploration Transportation System</td>
<td>Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.</td>
<td>ISRU can reduce mass launched from Earth</td>
<td>ISRU can reduce mass launched from Earth</td>
</tr>
<tr>
<td>6</td>
<td>Space station</td>
<td>International Space Station</td>
<td>Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space</td>
<td>In Space &amp; In Situ manufacturing / In Situ Logistics and Repair Capability</td>
<td>In Space &amp; In Situ manufacturing / In Situ Logistics and Repair Capability</td>
</tr>
<tr>
<td>7</td>
<td>Shuttle</td>
<td>Space Shuttle</td>
<td>Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration</td>
<td>In Space &amp; In Situ manufacturing / In Situ Logistics and Repair Capability</td>
<td>In Space &amp; In Situ manufacturing / In Situ Logistics and Repair Capability</td>
</tr>
<tr>
<td>8</td>
<td>Universe</td>
<td>Universe Exploration</td>
<td>Explore the universe to understand its origin, structure, evolution, and destiny.</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>9</td>
<td>Earth</td>
<td>Earth Science and Applications from Space</td>
<td>Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>10</td>
<td>Sun-Solar System</td>
<td>Sun-Solar System Connection</td>
<td>Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>11</td>
<td>Aero</td>
<td>Aeronautical Technologies</td>
<td>Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.</td>
<td>ISRU can provide propellants for planetary fliers</td>
<td>ISRU can provide propellants for planetary fliers</td>
</tr>
<tr>
<td>12</td>
<td>Education</td>
<td>Education</td>
<td>Use NASA missions and other activities to inspire and motivate the nation’s students and teachers, to engage and educate the public, and to advance the nation’s scientific and technological capabilities.</td>
<td>Use ISRU principles to educate, inspire and motivate</td>
<td>Use ISRU principles to educate, inspire and motivate</td>
</tr>
<tr>
<td>13</td>
<td>Nuclear</td>
<td>Nuclear Systems</td>
<td>Utilize nuclear systems for the advancement of space science and exploration.</td>
<td>Utilize nuclear power for ISRU systems</td>
<td>Utilize nuclear power for ISRU systems</td>
</tr>
</tbody>
</table>
ISRU State of Art (SOA)

- In all areas of ISRU, significant terrestrial capabilities & hardware exist

- Resource Extraction
  - Some sub-capabilities have been demonstrated, including scooping of regolith samples on the Moon and Mars, coring of regolith samples on the Moon, and grinding and analysis of rock samples on the Moon and Mars.
  - Significant work has been performed on acquiring and separating Mars atmospheric resources

- Material Handling & Transportation
  - Extra-terrestrial experience in handling and transporting native materials is very limited for Moon (Apollo samples were manually manipulated for encapsulation were transported in small containers aboard the Lunar rover vehicle and back to Earth) and Mars (samples were/are robotically manipulated for limited analysis and disposal by Viking, MER, etc.)
  - Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge:

- Resource Processing
  - Lunar ISRU has a 30 year history of laboratory testing, but little development money for systems level development.
  - Mars ISRU has had more development over the last decade but focus has been atmospheric processing

- Manufacturing with In-Situ Resources
  - Extensive microgravity materials processing experiments have been done in space in Apollo, Skylab, and Spacelab,
  - Paper studies show that 90% manufacturing materials closure can be obtained from lunar materials and 100% from Mars materials.
  - Feasibility efforts for fabrication of photovoltaic cells and arrays out of lunar derived materials have been performed
**ISRU SOA (2)**

### Surface Construction
- **Site planning:** Lunar/Mars topography data sets are partially available, some geophysical characterization is available (Apollo/Mars programs), and Lunar regolith and properties for upper 2 meters is available from Apollo program.
- **Structure & Habitat Fabrication:** Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, and laboratory tests have been performed on lunar construction materials (waterless concretes, glass fibers and rods, sintered bricks, etc.).
- **Radiation protection:** MMOD concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel).
- **Structure & Site Maintenance:** In space maintenance and repair are evolving, self-healing materials are currently being tested, EVA and IVA repairs are regularly performed on the International Space Station, and tile repair tools and materials are being developed as part of return to flight activities for the Space Shuttle.
- **Landing & Launch Site:** Apollo style landings on the Moon showed ejecta occurred but did not threaten vehicle (23 metric Ton landed Mass).

### Surface Consumable/Product Storage & Distribution
- Limited size and capacity cryo-coolers have flown (science instruments).
- Cryogenic fluid storage systems has flown, but for limited durations and not with integrated liquefaction systems.
- Automatic and EVA fluid couplings have flown on ISS; Helium II coupling built but not flown.

### ISRU Unique Test and Certification
- **Simulants:** ~25 tons of JSC-1 lunar simulant produced in early 90’s, and Martian physical simulant established and used in testing.
- Lunar and Mars environmental chambers exist to support ISRU development.
- Micro/partial gravity testing for short durations exist through use of drop towers (5.2 sec max), aircraft, and sounding rockets.
- Micro-g long duration testing might be possible through use of ISS glove-box (.9m x .5m x .4m) or ISS integrated experiment rack.
ISRU Gaps

- Dust mitigation
- Low-gravity effects on solid material handling, processing, manufacturing, and construction

Resource Extraction, Handling, & Transportation
- Better definition of target material and resource information are required
  - Current data useful only for prospecting
  - Effects of Lunar and Martian environments on equipment technologies unknown
- Lunar and Mars excavation, material handling, and transportation are very immature

Resource Processing:
- Development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment is required
- Further processing technology development required to meet operating life goals and increase mass/power/volume efficiency of ISRU
- Further integrated system build-up and testing required to meet packaging goals
- Processing of manufacturing and construction feedstock is very immature

Manufacturing
- Development of power generation, management, and distribution from in-situ resources and feedstock is very immature
ISRU Gaps (2)

- **Surface Construction**
  - Scale and resolution for the moon and Mars for detailed site planning is insufficient
  - Architecture and civil engineering disciplines for non-terrestrial surface applications are immature
  - Tele-operation and/or automation of robotic construction processes is very immature
  - In situ production of spares and parts in space is very immature

- **Surface Consumable/Product Storage & Distribution**
  - High-capacity, long-life cryocoolers for cryogenic propellants
  - Deployable tanks and distribution systems for cryogenic fluids and high pressure gas.
  - Long life compressors and motors for extraterrestrial applications
  - Integrated, large scale liquefaction and long term storage of cryogenics with flight weight systems/components
  - Dust insensitive fluid couplings and leak detection in open vacuum or low atmospheric environments

- **ISRU Unique Test & Certification**
  - Granular material modeling requires a ‘mathematical breakthrough’ to accurately model all physical behaviors
  - Vacuum chambers and wind tunnels willing to allow introduction of simulants on large scale
  - Remote equipment to handle, distribute, charge, etc. simulants within vacuum chamber
  - Chambers with integrated test environments - thermal, vacuum/atmosphere, dust, and solar
  - Cost efficient long term environmental testing
  - Chambers to simulate permanently shadowed craters at lunar poles
ISRU Risks

- **Resource Risks** (due to incomplete prospecting)
  - Potential resource is not available
  - Resource not available at landing site
  - Resource is present, *BUT*
    - Form is different than expected (concentration, state, composition)
    - Location is different than expected (depth, distribution)
    - Unexpected impurities

- **Technical Risks**
  - Level of maintenance & repair unknown
  - Uncertainty in performance and amount regolith excavation required
  - Sealing for regolith processing systems.
  - System reliability.
    - More complex systems are more likely to fail and more difficult to fix.
    - Robustness and flexibility often conflict, though both are needed in new environments.
    - Scaling issues are non-linear and non-trivial.
    - Difficult to test with simulations; field experience required (more=better).
  - Effects of lunar and Mars environmental conditions.

- **Political uncertainty.**
  - Reliance on ISRU and resources seems to be a liability vs an asset by current mission planners
  - Many terrestrial resource extraction projects have been canceled due to changes in political climate.
ISRU Roadmap Team Recommendations

- Human mission architectures need to plan for use of ISRU products from start of planning
  - Can strongly influence mission phases, locations, and element designs to achieve maximum benefit of ISRU
  - Early investigation of Lunar and Mars resources, especially water can significantly change human exploration approach

- Piggyback resource assessment requirements and instruments on Science missions to Moon and Mars
  - Complementary/supplementary to science goals.
  - Assessment provides crucial information for all aspects of ISRU

- Early ISRU process demonstrations in relevant environment in logical and orderly progression
  - Minimize risk and maximize benefits of incorporating ISRU into mission architectures
  - Not all demonstrations need to be dedicated missions

- Maximize use of common technologies, hardware, and mission consumables between ISRU, propulsion, mobile power, life support, and EVA suit systems

- All systems must be designed “up front” for repairability or use of spare parts manufactured with in situ processes and resources

- Initiate government efforts to promote commercial development and use of ISRU
Summary/ Forward Work

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for CRM Title capability
- Make changes to CRM Title roadmaps to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the CRM Title Capability Roadmap
- Prepare for 2\textsuperscript{nd} NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?