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

- 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

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

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

Coordinators

Directorate: John Mankins, ESMD
APIO/JPL: Rob Mueller, Affiliation

- **Further list of volunteers for each ISRU Element team**
- **Broad ISRU industry & academic community** (Space Resources Roundtable & STAIF Conferences)

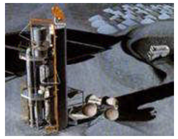
What are Space Resources?

- 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

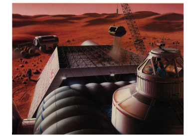
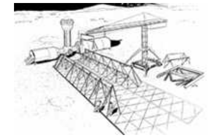
Uses of Space Resources for Robotic & Human Exploration





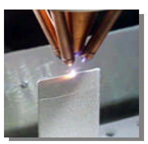

Mission Consumable Production

- ➢ **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

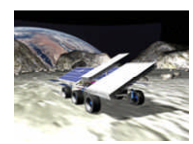
Surface Construction

- ➢ **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

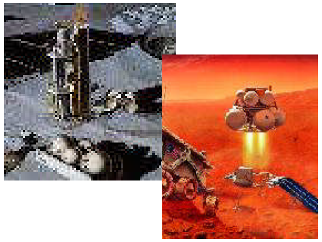
- ➢ **Spare parts manufacturing**
- ▪ Locally integrated systems & components (especially for increasing resource processing capabilities)
- ▪ High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)


Space Utilities & Power

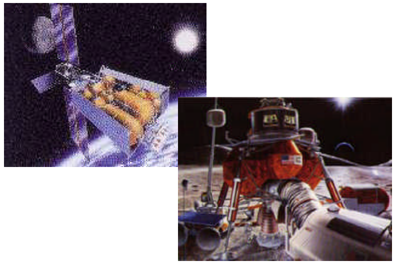
- ➢ **Storage & distribution of mission consumables**
- ▪ Thermal energy storage & use
- ➢ **Solar energy** (PV, concentrators, rectennas)
- ➢ **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

Benefits of ISRU: Critical for Affordable, Flexible, & Sustainable Exploration



Mass Reduction

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

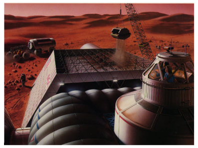


Cost Reduction

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

Space Resource Utilization

Risk Reduction & Flexibility



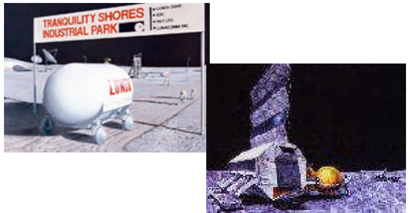
- Number of launches & mission operations reduced
- Reduces dependence on Earth
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding

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

- 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



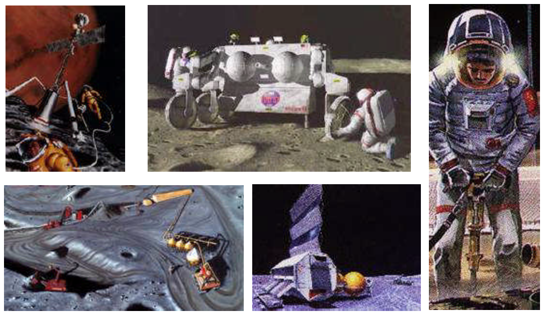
NASA Vision & Exploration Challenges

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***

Strategic Challenges	How ISRU Meets Challenge
Margins & Redundancy	**Use of common technologies/hardware and mission consumables enables** swapping/cross use
	See ASARA
Reusability	**Production of mission consumables (propellants, fuel cell reagents, science gases, etc.) enables** reuse **of typical single use assets**
Modularity	**ISRU utilizes common technologies/hardware with life support, fuel cell power, and propulsion systems**
As Safe As Reasonably Achievable (ASARA)	**Use of** functional/dissimilar redundancy **for mission critical systems (such as life support) increases mission safety**
	ISRU can eliminate aborts **which may occur without capabilities: life support, power, spare parts, etc.**
	ISRU can reduce number of launches and mission operations increasing mission success probability
	Use of in-situ materials for radiation shield enable lower levels of radiation exposure **compared to Earth provided shielding**
Robotic Networks	**ISRU incorporates robotic networks to enable ISRU capabilities before human occupation**
Affordable Logistics Pre-Positioning	**ISRU enables** large mass leveraging **of pre-positioned hardware into usable mission products and consumables (space parts, propellants, life support gases, etc.)**
Energy Rich Systems & Missions	**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)**
Access to Surface Targets	**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**
Space Resource Utilization	**All of above**

In-Situ Resource Utilization Elements

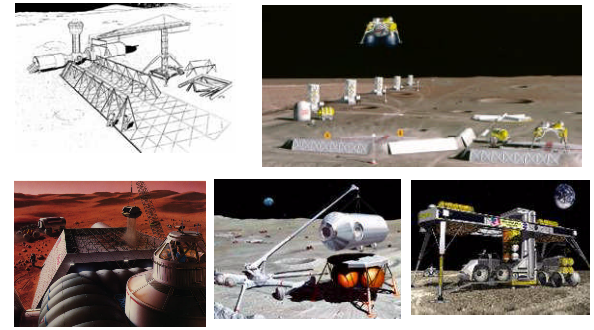
In-Situ Resource Extraction & Transport



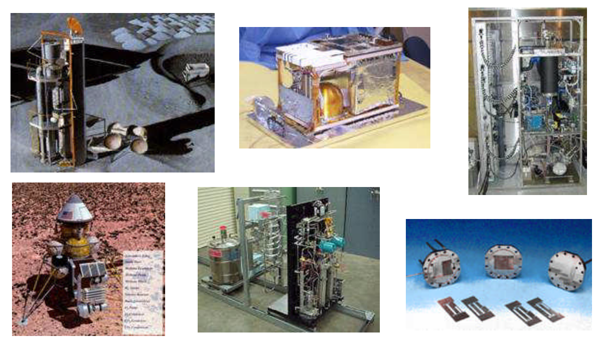
Involves assessment of resources, and extraction, excavation, and delivery of resources in low and micro-g environments, including the simple extraction and separation of resources from bulk resources

Surface Construction

Involves processes and operations for constructing elements & infrastructure on planetary surfaces using materials produced from planetary resources

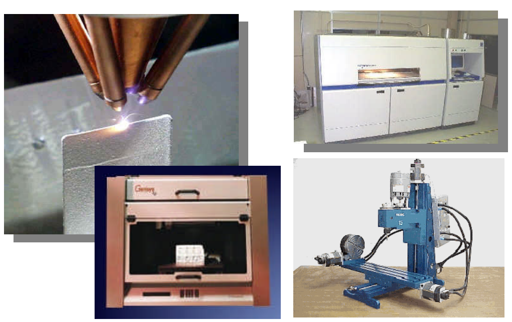


Resource Processing



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

Surface Manufacturing w/ Space Resources



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

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

Team 13: In-Situ Resource Utilization

In-Situ Resource Utilization 13.0

Chair: Jerry Sanders/JSC
Co-Chair: Mike Duke (CSM)

- **Resource Extraction** 13.1
  Chair: L. Gertch/UMR & Don Rapp/JPL
  - Resource Assessment 13.1.1
  - Resource Acquisition 13.1.2
  - Resource Beneficiation 13.1.3
  - Site Management 13.1.4
- **Material Handling & Transportation** 13.2
  Chairs: Kurt Sacksteder/GRC & Dale Boucher/NORCAT
  - 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
- **Resource Processing** 13.3
  Chairs: Bill Larson/KSC & Larry Clark/LMCO
  - 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
  - Common Critical Components 13.3.4
- **Surface Manufacturing with In-Situ Resources** 13.4
  Chair: Peter Curreri/MSFC & Ed McCullough/Boeing
  - 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
- **Surface Construction** 13.5
  Chair: Kris Romig/JSC & Eric Rice/Orbitec
  - 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 ISRU Product & Consumable Storage and Distribution** 13.6
  Chair: Robert Johnson/KSC & Robert Zubrin/Pioneer Ast.
  - 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
- **ISRU Unique Development & Certification Capabilities** 13.7
  Chair: Diane Linne/GRC & Mike Downey/JSC
  - Modeling & Standards 13.7.1
  - Simulants 13.7.2
  - Unique Test Environments (1-g) 13.7.3
  - Reduced Gravity Test Environments 13.7.4

Roadmap Charter Assumptions With Other Capabilities

- 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
  - 6
- *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

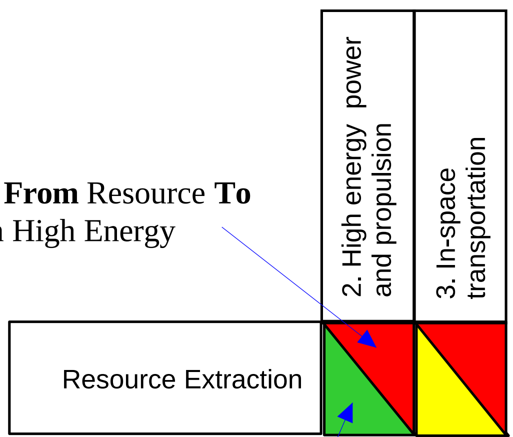
- H_2 & ^3He for NTR & fusion; Ar for electric
- Solar array and collector manufacturing & assembly
- Rectenna fabrication for orbital power beaming
- Thermal storage material production & fabrication
- Radiation shields for nuclear reactors

Capability Products To ISRU

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

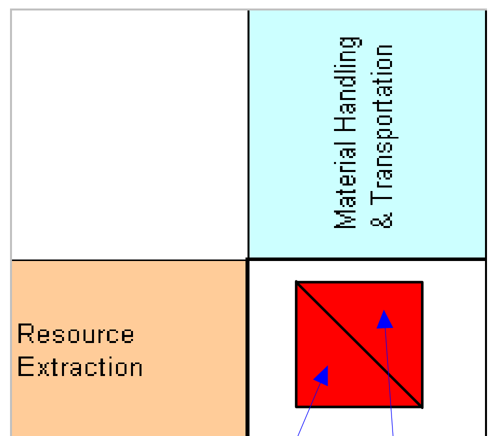
ISRU Element to Other Capabilities

Criticality **From** Resource **To** Extraction High Energy



Criticality **From** High Energy **To** Resource Extraction

ISRU Element to Other Element

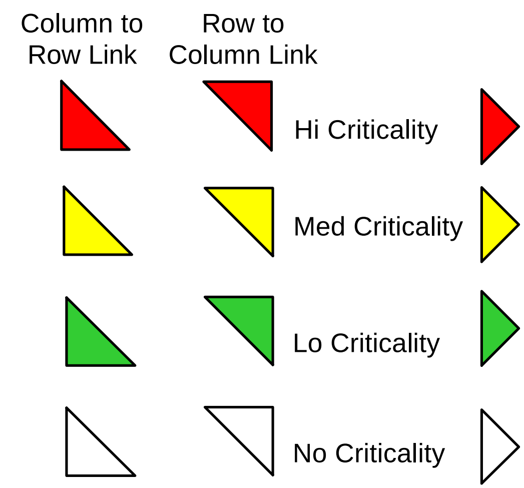


Criticality **From** Material Handling & Transportation **To** Resource Extraction

Criticality **From** Resource Extraction **To** Material Handling & Transportation

Symbol Key

- Color Denotes Criticality
- Arrow Point Denotes Direction



ISRU Product Interdependency With Other Capabilities

Team 13: In-Situ Resource Utilization

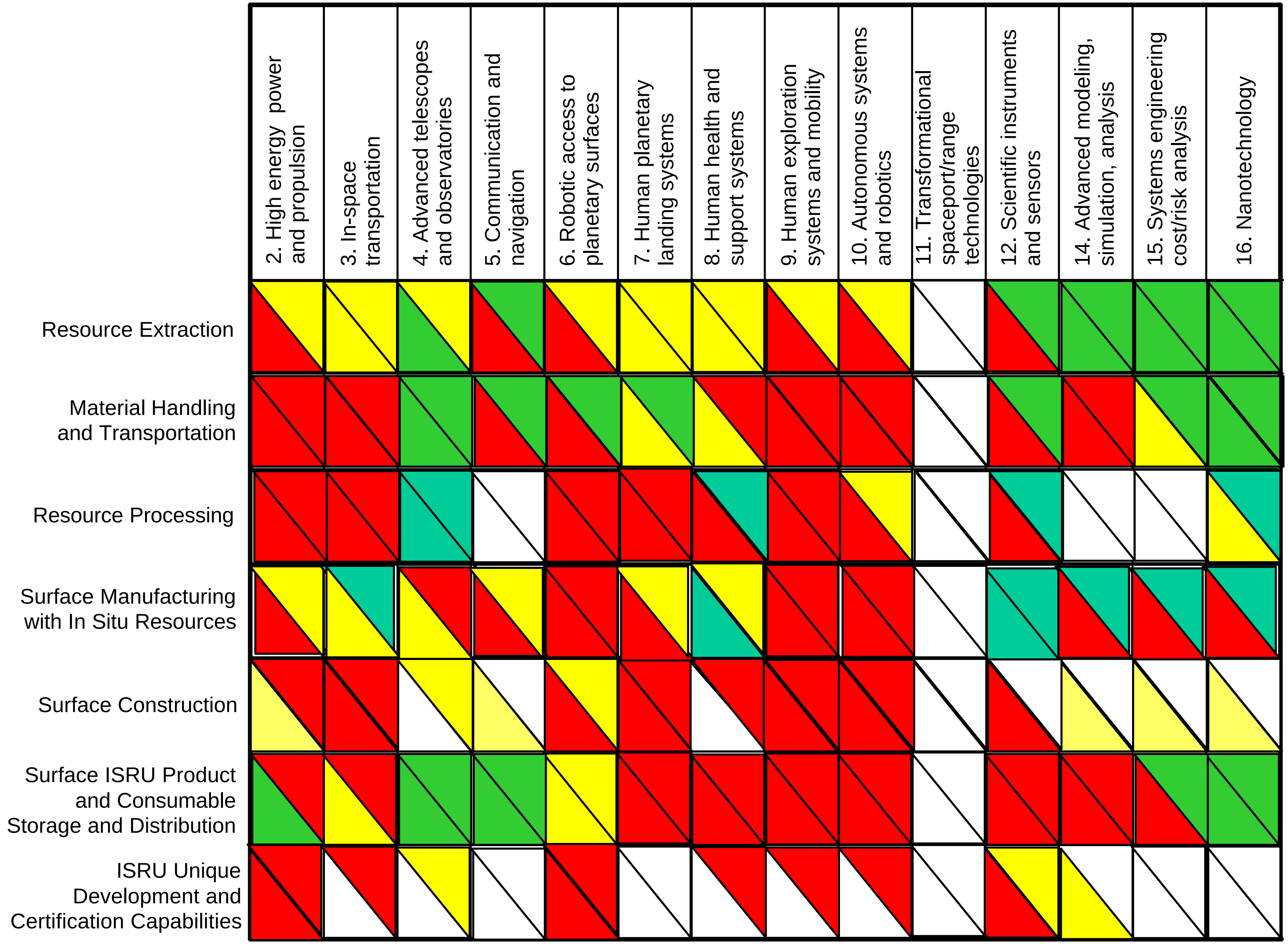
ISRU Products To Other Capabilities	Capability	Capability Products To ISRU
• H_2 & ^3He for NTR & fusion; Ar for electric • Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication • Radiation shields for nuclear reactors • Power cable deployment; in-situ provided power management & distribution	High-Energy Power & Propulsion (2)	• Initial solar & nuclear power to support power-intensive ISRU activities • Mobile/high-density power sources.
• Propellant production and pressurant/purge gases for lander reuse and in-space depots • Aeroshells from Regolith	In-Space Transportation (3)	• ISRU-compatible propulsion • Delivery of ISRU products to sites of exploration and in-space depots
• Shaping crater for collector • In-situ construction and fabrication; foundation design & peparation • Gases for inflatable structures • Raw materials for space based observatory manufacture	Advanced Telescopes & Observatories (4)	
• Raw materials for infrastructure	Telecommunications and Navigation (5)	• Mobile equipment navigation. • Fast communication among systems components.
• 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	Robotic Access to Planetary Surfaces (6)	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Landing pads/plume debris shielding • Propellant production/storage/transfer for lander reuse	Human Planetary Landing Systems (7)	• Precision landing • Delivery of ISRU capabilities to sites of exploration

ISRU Product Interdependency With Other Capabilities (Cont.)

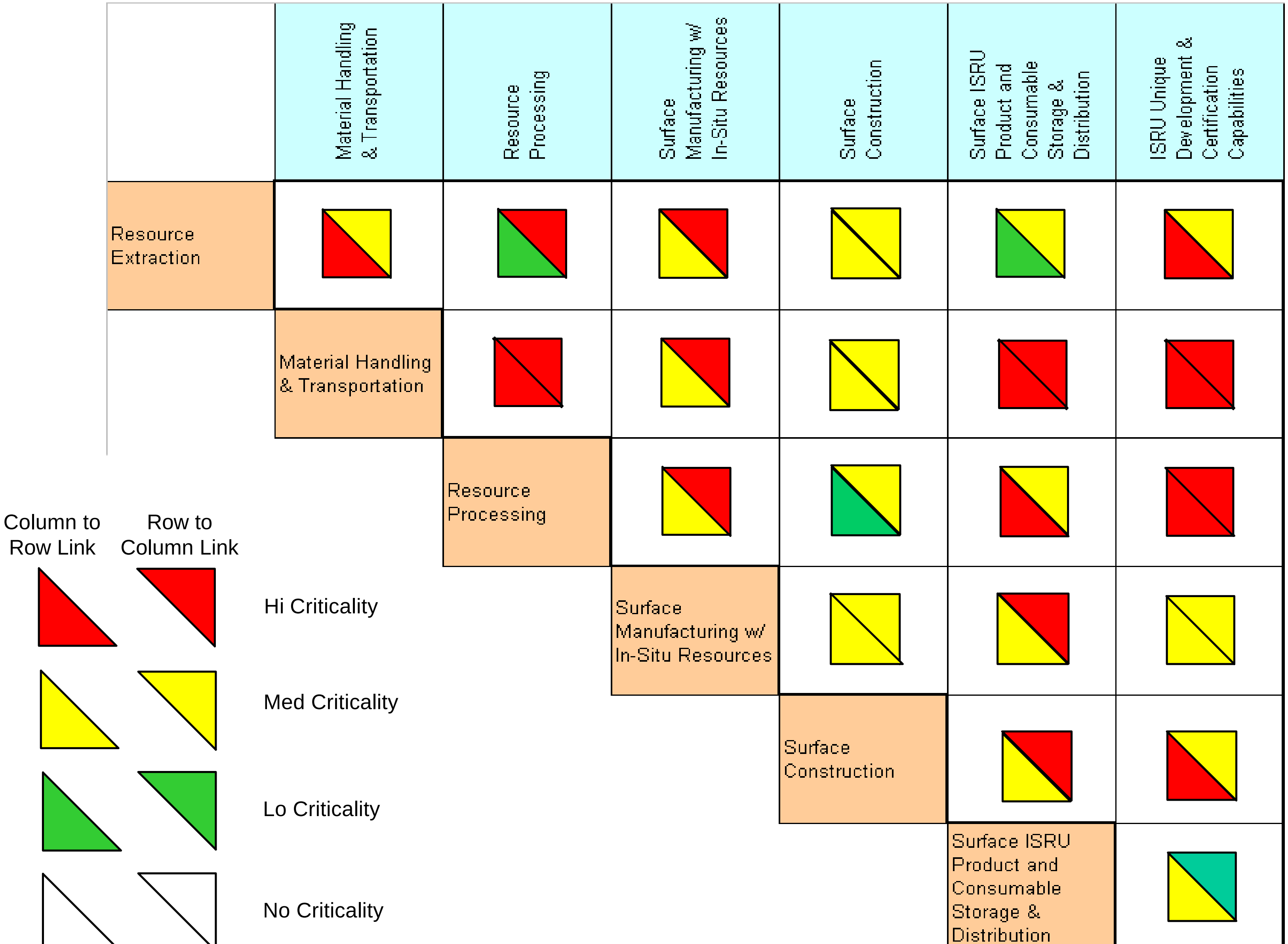
Team 13: In-Situ Resource Utilization

ISRU Products To Other Capabilities	Capability	Capability Products To ISRU
• Habitat/shelter fabrication • Gases for inflation & buffer gases • Life support consumable production for backup • Radiation & micro-meteoriod debris shields from in-situ material • Soil & bio-feedstock for plant growth • Materials for in-situ manufacturing	Human Health and Support Systems (8)	• Carbon-based waste products as resource for ISRU • Common hardware for possible modularity with ISRU systems
• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 production for EVA • Soil stabilization/dust control • Roadway infrastructure • Engineering properties of regolith	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Fuel cell reactants for surface vehicles and aero-bots • New & replacement parts for robotic systems	Autonomous Systems & Robotics (10)	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Gases and explosives for science equipment • Increased sample and measurement density for science studies.	Scientific Instruments & Sensors (12)	• Resource location & characterization information • Self Calibrating or Extended Calibration Life Sensors
	Advanced Modeling, Simulation, & Analysis (14)	• Resource formation models. • Mining and reclamation method evaluation. • Resource delivery and distribution models. • Granular material performance models.
	Nano-Technology (16)	• Nanotube catalysts for Microchemical Reactors

ISRU Element Interdependency With Other Capabilities



ISRU Element Interdependency Summary



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:

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

- 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 extend 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

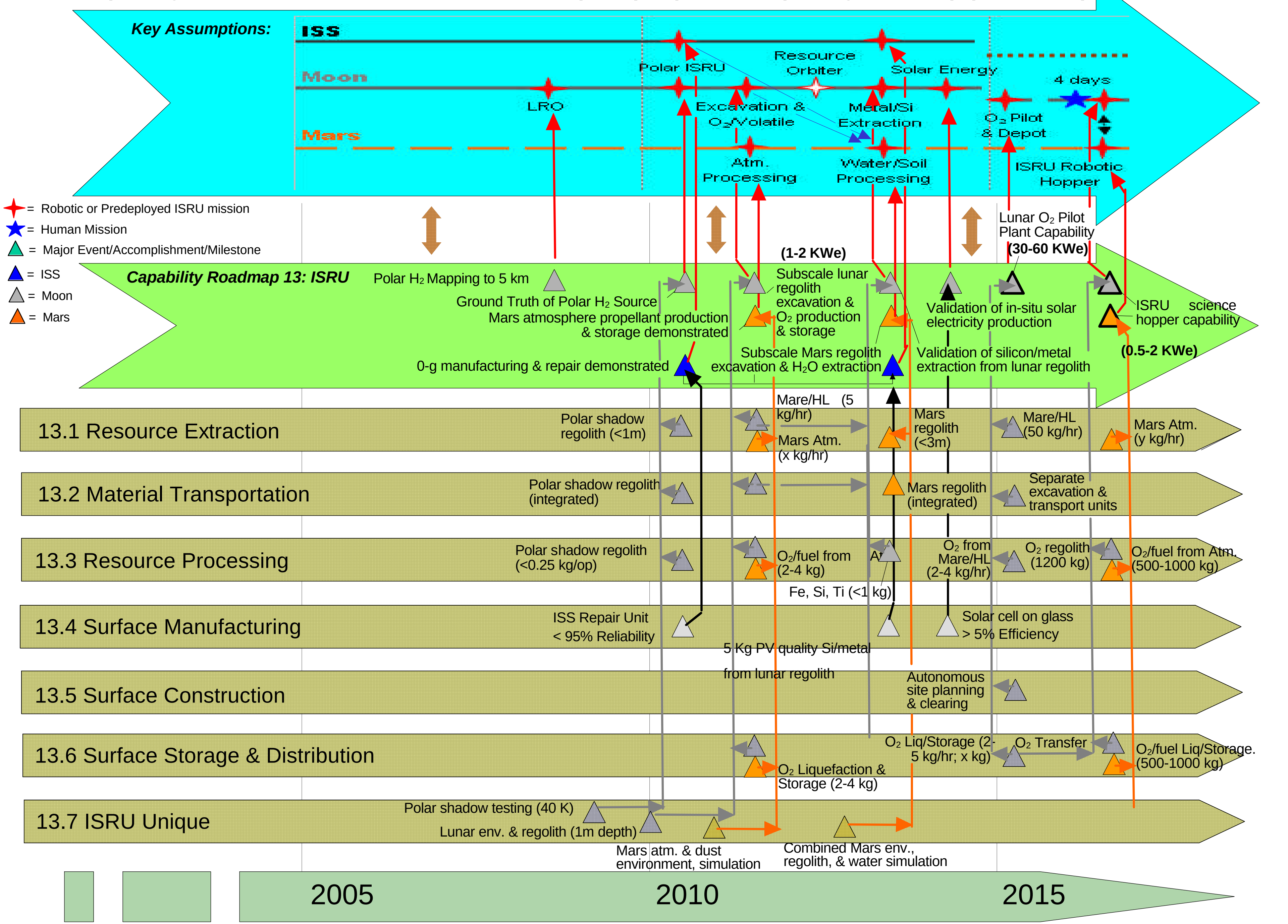
    Perform ISRU pilot operations in Spiral 2 to enhance missions and support full use at start of Spiral 3
  - Develop lunar ISRU as a precursor to Mars missions as well as enable sustained human lunar operations

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

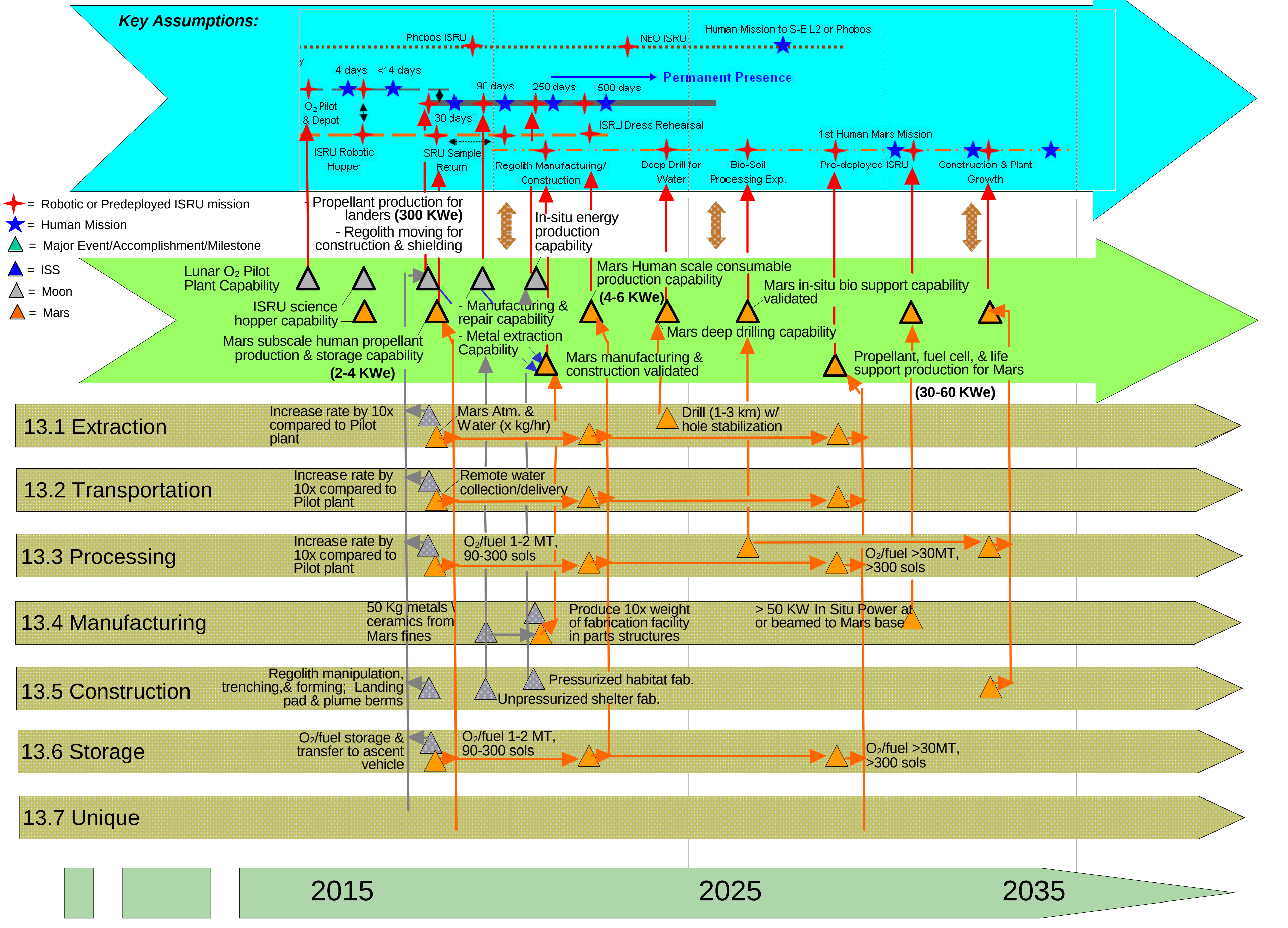
ISRU Usage & Incorporation Assumptions

- Spiral 2 & beyond
  - Surface mobility systems will utilize In-situ produced fuel cells reagents
  - ISRU systems sill 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 regolth
  - 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)



Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2015 to 35)



Top-Level ISRU Development & Integration Strategy

- **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 at 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; 1/3rd 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.)

ISRU-Emphasized Architecture Benefits

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

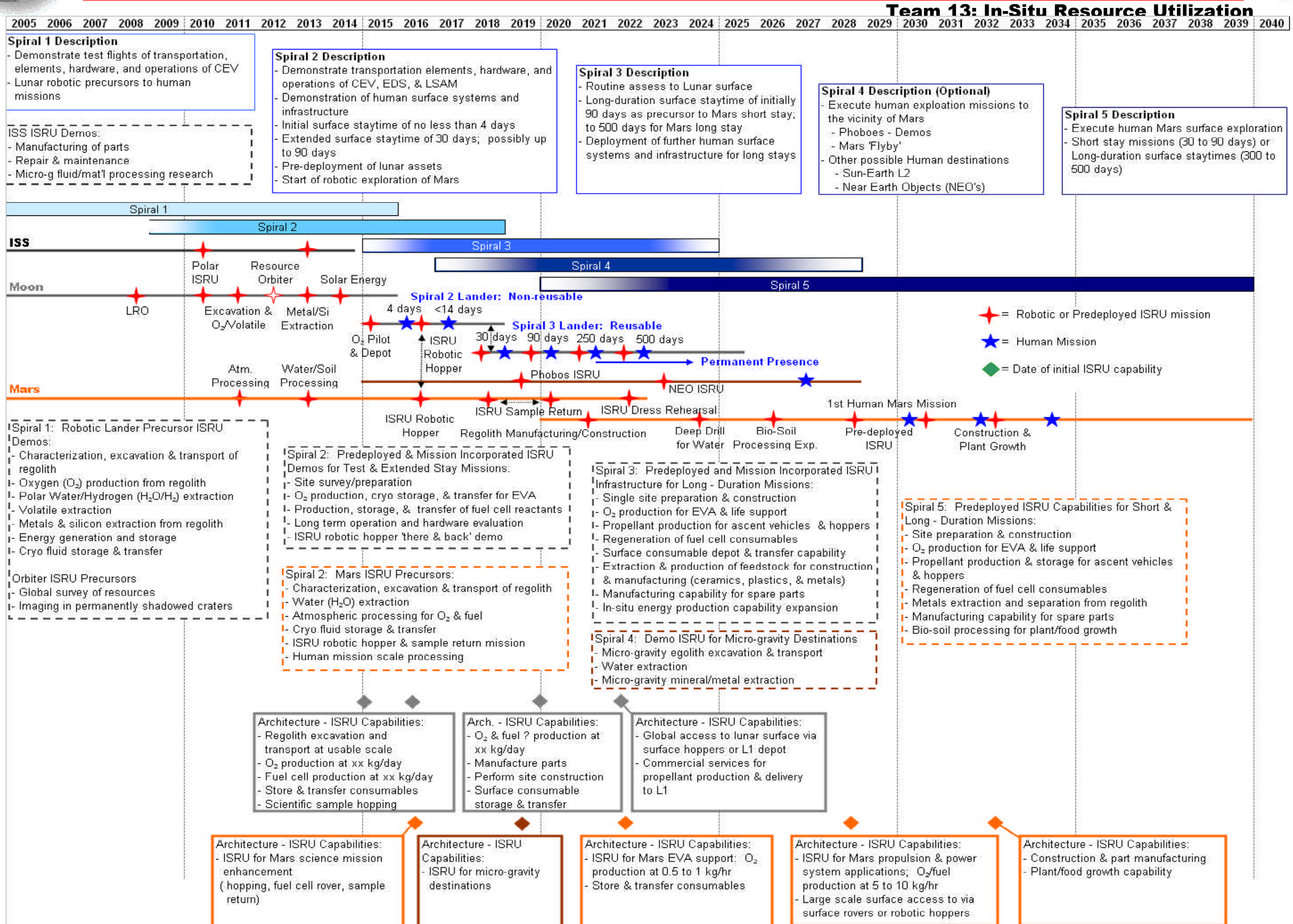
Spiral 4 Benefits:

- 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 insitu capabilities, lower radiation, reduced number of mission events, etc.)

Notional ISRU-Supported Mission Timeline



ISRU Architecture Applications & Capabilities

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 (O_2) production from regolith (possibly propellant for Lunar sample return)
  - Polar Water/Hydrogen (H_2O/H_2) extraction
  - Volatile extraction (H_2, He/^{3}He, N_2, 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

ISRU Arch. Applications & Capabilities (Cont.)

- Spiral 2 Lunar ISRU Demonstrations & Mission Enhancements
  - Scalable excavation & transport of regolith
  - Site survey/preparation
  - Production, storage, & transfer of oxygen (O_2) 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 (H_2O) extraction
  - Atmospheric processing for O_2 & fuel
  - Cryo fluid storage & transfer
  - ISRU robotic hopper & sample return mission
  - Human mission scale processing

ISRU Arch. Applications & Capabilities (Cont.)

- Spiral 3 Lunar ISRU Mission Applications
  – Single site preparation & construction (berms, radiation shielding, habitat deployment, etc.)
  – 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
  – 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.

Propellant to Earth-Moon L1 for Moon/Mars

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 electro-magnetic 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

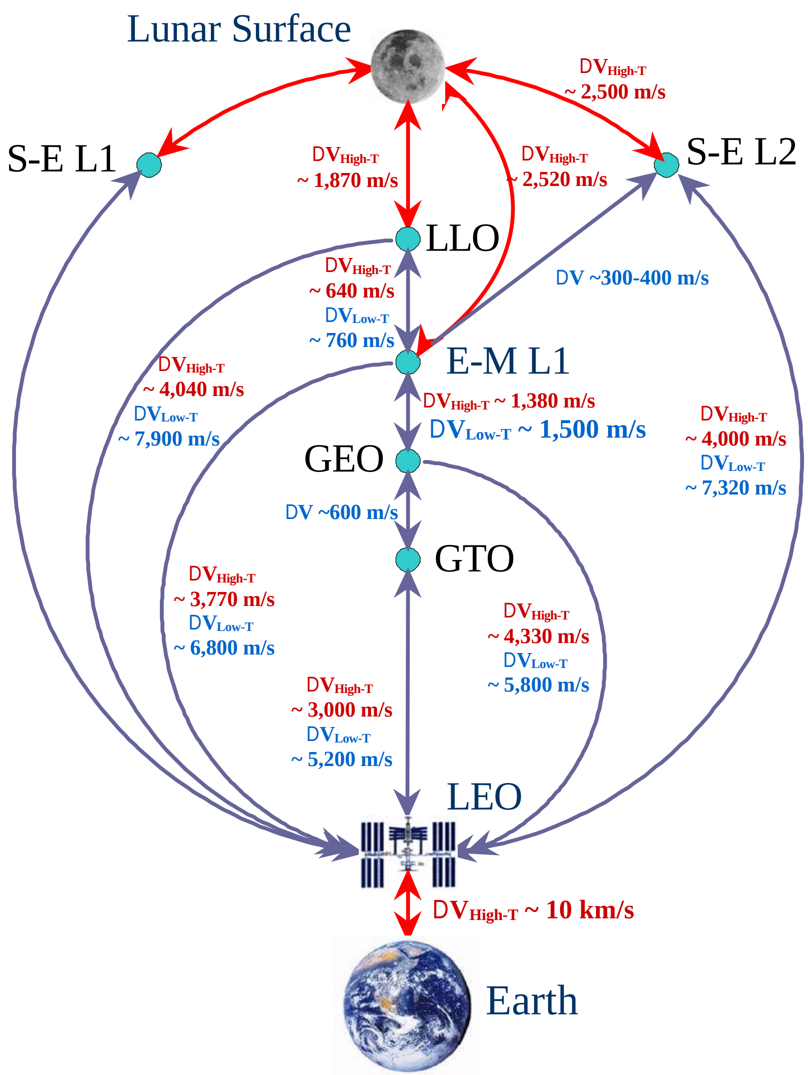
Additional Spiral 3 Benefits:

- 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]

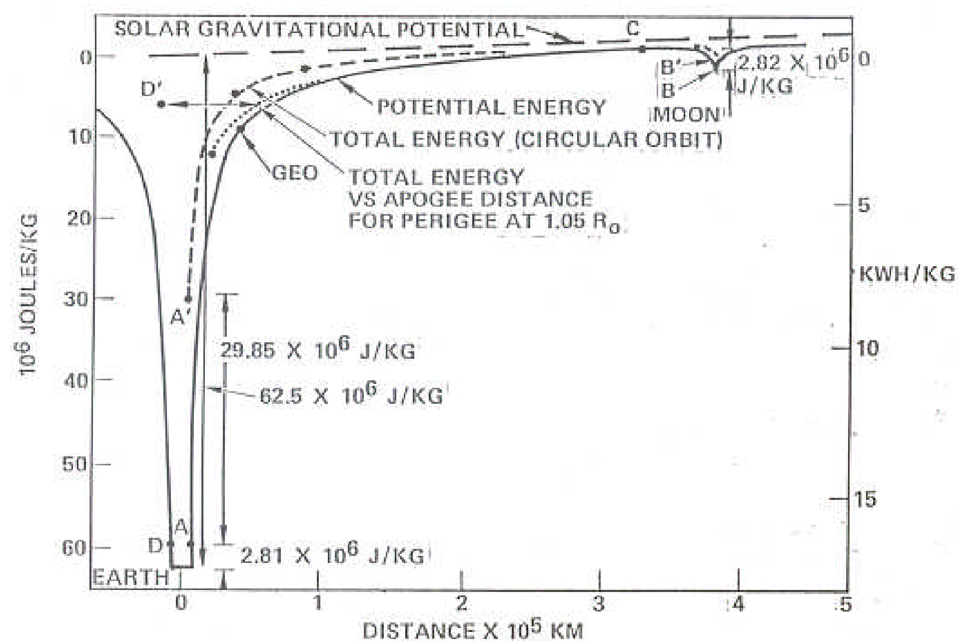
Additional Spiral 5 Benefits

- 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



ISRU Sub-Element 13.1 Resource Extraction

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

Resource Extraction Capability Roadmap Team

Co-Chairs

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

Government: NASA

- Allen Wilkinson, GRC
- David McKay, JSC
- Kris Romig, JSC
- Phil Metzger, KSC
- Ron Schlagheck, MSFC
- Chuck Owens, MSFC
- Paul Carpenter, MSFC

Government: Other

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

Industry

- Richard Dissly, Ball Aerospace
- Kevin Ashley, Bechtel Mining & Metals
- Ed McCullough & Kurt Klaus, Boeing
- 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

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

Team 13: In-Situ Resource Utilization

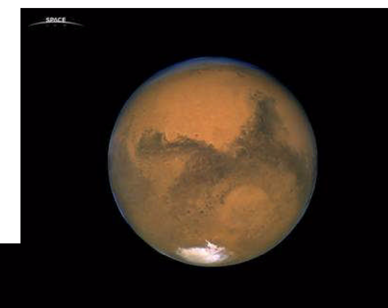
- In-Situ Resource Utilization 13.0
  - Resource Extraction 13.1
    - Resource Assessment 13.1.1
      - Prospecting 13.1.1.1
      - Delineation 13.1.1.2
      - Development 13.1.1.3
    - Resource Acquisition 13.1.2
      - Atmospheric Gases 13.1.2.1
      - Underground Liquids and Gases 13.1.2.2
      - Regolith 13.1.2.3
      - Rock 13.1.2.4
      - Mixed Materials 13.1.2.5
      - Excavated Openings as Product 13.1.2.6
      - Waste Materials 13.1.2.7
    - Resource Beneficiation 13.1.3
      - Change of Phase 13.1.3.1
      - Particle Size Change 13.1.3.2
      - Separation 13.1.3.3
      - Internal Materials Handling 13.1.3.4
    - Site Management 13.1.4
      - Site Planning 13.1.4.1
      - Dust Control 13.1.4.2
      - Anchoring 13.1.4.3
      - Ground Stability Control 13.1.4.4
      - Transportation and Storage 13.1.4.5
      - Monitoring 13.1.4.6
      - Auxiliary Operations 13.1.4.7
      - Waste Management 13.1.4.8
      - Site Reclamation 13.1.4.9

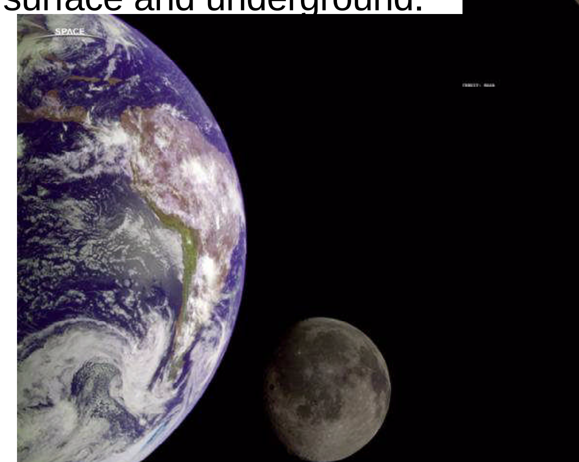
Blue outline = major capability needed for 2005-2035

Dashed outline = commonality with other capability(ies)

Attributes and Benefits of Resource Extraction

- Provides <u>feedstock</u> 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 <u>raw materials</u> for:
  - **Bulk radiation shielding**.
  - Construction materials.
- <u>Excavates</u> 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.
- <u>Enables</u> power generation:
  - Materials to produce solar power cells.
  - Materials to produce fuel cell reagents.
  - ^{3}He for nuclear fusion reactors.
- <u>Leverages</u> initial equipment.
  - Provides these materials for less mass than shipping finished products from Earth.





Requirements and Assumptions for Resource Extraction

- 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

- Raw materials for:
  - Propellants.
  - Fuel cell reagents.
  - System components.
  - Infrastructure fabrication.

(to: High-Energy Power & Propulsion; In-Space Transportation; Advanced Telescopes & Observatories; Telecommunications and Navigation; Robotic Access to Planetary Surfaces; Human Planetary and Landing Systems)

- Waste re-use.
- Shelter excavation.
- Raw materials for life support.

(to: Human Health and Support Systems)

Products To 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.

Resource Extraction Commonality-Dependency With Other Capabilities

Team 13: In-Situ Resource Utilization

Products From Resource Extraction	Capability	Products To Resource Extraction
• Raw materials for: • Propellants. • Fuel cell reagents. • System components. • Infrastructure fabrication.	Human Exploration Systems and Mobility (9)	• Human interfacing with Resource Extraction systems.
	Autonomous Systems and Robotics (10)	• Autonomous and robotic systems for all phases of Resource Extraction.
	Transformational Spaceport and Range (11)	• Equipment, parts, supplies, etc. delivery.
• Increased sample and measurement density for science studies.	Scientific Instruments and Sensors (12)	• Resource Assessment data.
	Advanced Modeling, Simulation, & Analysis (14)	• Resource formation models. • Mining and reclamation method evaluation. • Resource delivery and distribution models. • Granular material performance models.
	Systems Engineering Cost & Risk Analysis (15)	• Extraction system analyses.
	Nanotechnology and Advanced Concepts (16)	

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

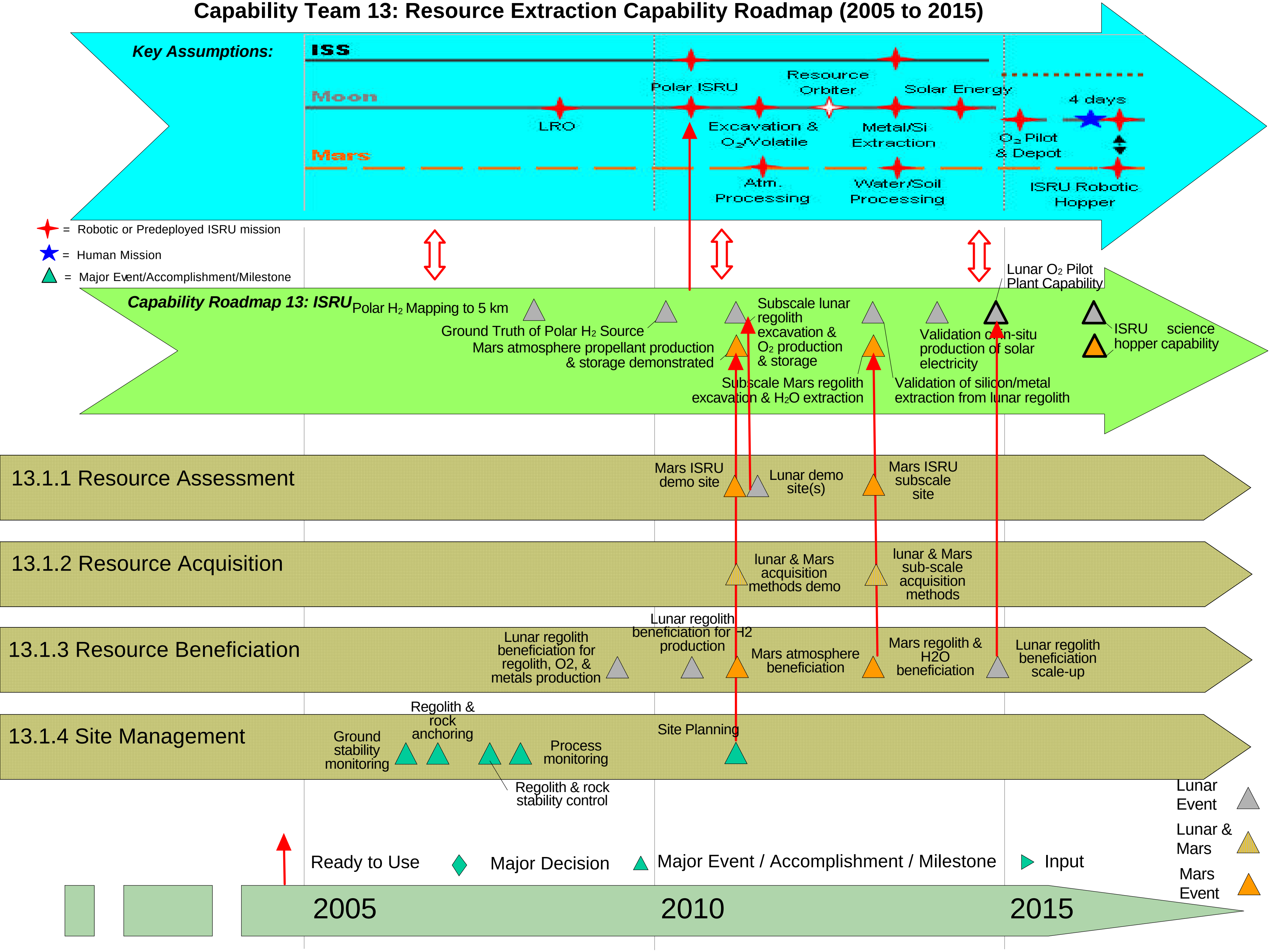
Resource Processing
- Feedstock

Surface Manufacturing
- Feedstock

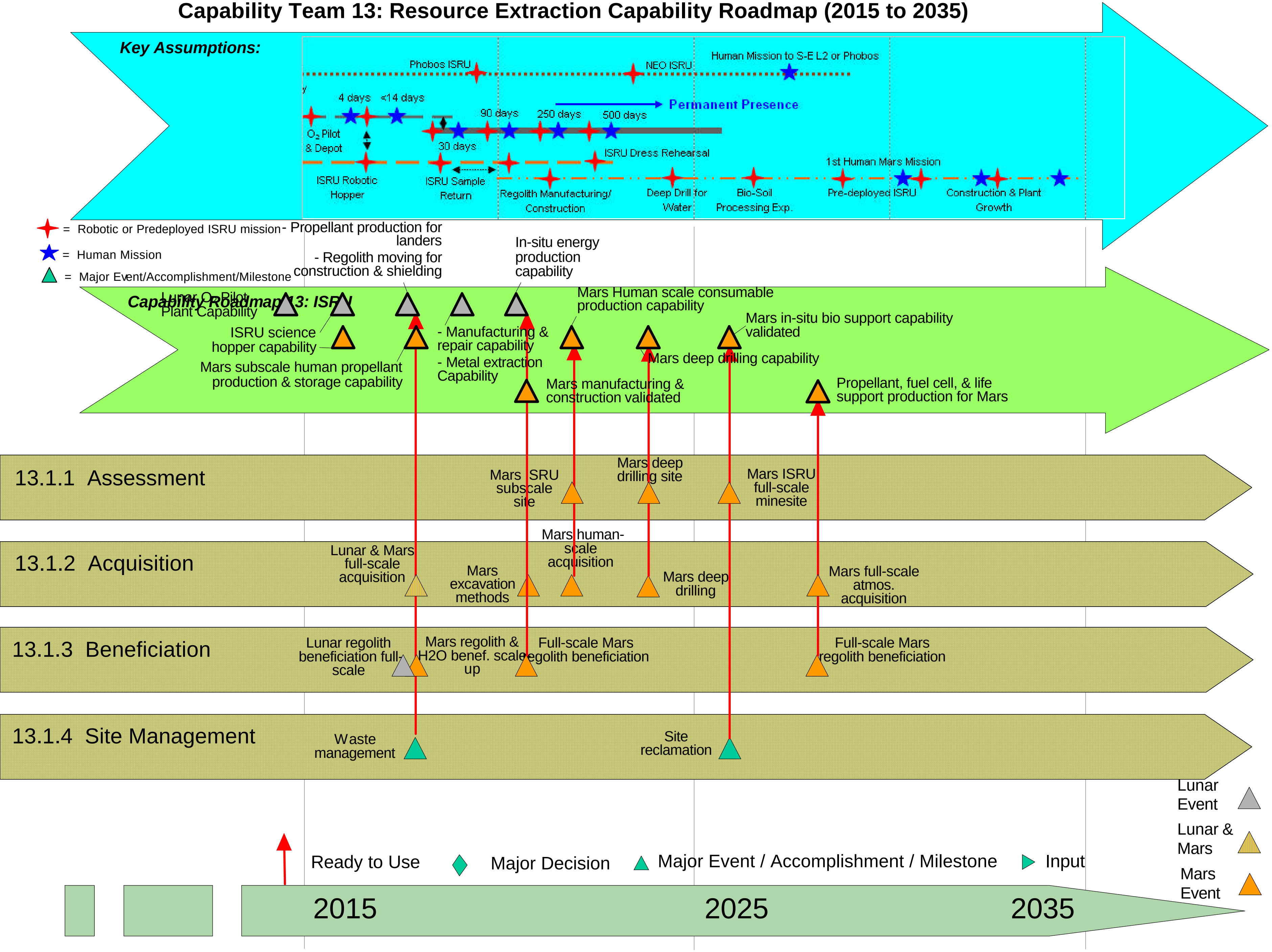
Product Storage & Distribution
- Ready-to-use gases and liquids

Surface Construction
- Ready-to-use construction materials

Capability Team 13: Resource Extraction Capability Roadmap (2005 to 2015)



Capability Team 13: Resource Extraction Capability Roadmap (2015 to 2035)



Current State-of-the-Art for Capability 13.1 Resource Extraction

- 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

Team 13: In-Situ Resource Utilization

Assess

Acquis

Benef

Manage

Capability	Key Technologies or Sub-Capabilities	Readiness Assessment		
		CRL	R&D3	Need Date
Prospecting and Delineation	Field Sampling Technologies	1-7	I	2007
	Mapping Technologies	1-7	III	2006
	Remote Geophysical Surveying Technologies	1-7	III	2005
	In Situ Geophysical Survey Technologies	1-7	III	2007
	Sample Analysis Technologies	1-7	III	2006
Prospecting, Delineation, and Development	Drilling Technologies	1-7	III	2007
	Human & Robotic Transportation Technologies	1-7	III	2010
	Pit and Trench Excavation Technologies	1-7	III	2008
Development	Tunnel/Shaft Excavation Technologies	2	III	2025
	Atmospheric Extraction Methods	2	II	2020
	Borehole Liquid & Gas Extraction Methods	2	III	2024
	Surface Extraction (Mining) Methods	1	II	2016
	Underground Extraction (Mining) Methods	1	II	2030
	In Situ Extraction Methods	1	III	2012
	Gas Collection Technologies	2	II	2016
	Dust Mitigation/ Control Technologies	0	IV	2012
	Granular materials performance models	0	III	2007
all Resource Acquisition capabilities	Human&Robotic Transportation Technologies	1-7	III	2010
	Continuous Materials Handling Technologies	2	II	2015
	Cyclic Materials Handling Technologies	3-7	III	2010
	Dust Mitigation/ Control Technologies	0	IV	2012
	Process Monitoring Technologies	1-4	III	2012
Atmospheric Gases Resource Acquisition	Atmospheric Extraction Methods	3	II	2020
Atmospheric Gases, Underground Liquids and Gases Resource Acquisition	Liquid and Gas Containment Technologies	3	II	2007
	Gas Collection Technologies	2	II	2016
Underground Liquids and Gases Resource Acquisition	Borehole Liquid & Gas Extraction Methods	1	III	2024
Underground Liquids and Gases, Regolith, and Rock	Drilling Technologies	1-7	III	2007
Regolith and Rock Resource Acquisition	Surface Extraction (Mining) Methods	1	II	2016
	Underground Extraction (Mining) Methods	1	II	2030
Regolith and Rock Resource Acquisition, and Excavated Openings as Product	Regolith & Rock Fragmentation Technologies	1	III	2008
	Regolith and Rock Excavation Technologies	1-2	III	2009
	Regolith and Rock Transport Technologies	1	II	2008
	Pit and Trench Excavation Technologies	1-7	III	2008
	Granular materials performance models	0	III	2007
Mixed Materials Resource Acquisition	*In situ* Extraction Methods	1	III	2012?

Maturity Level – Capabilities for 13.1 Resource Extraction

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Capability	Key Technologies or Sub-Capabilities	Readiness Assessment		
		CRL	R&D3	Need Date
Excavated Openings as Product	Tunnel/Shaft Excavation Technologies	2	III	2025
	Pit and Trench Excavation Technologies	1-7	III	2008
all Resource Beneficiation capabilities	Sample Analysis Technologies	1-7	III	2006
	Process Monitoring Technologies	1-4	III	2012
	Dust Mitigation/ Control Technologies	0	IV	2012
Beneficiation Change of Phase	Gas-Liquid Phase Change Technologies	1-3	II	2015
	Solid-Plasma Phase Change Technologies	1	III	?
	Solid-Gas Phase Change Technologies	1-3	II	2015
	Solid-Liquid Phase Change Technologies	1-3	II	2015
Beneficiation Particle Size Change	Solids Comminution Technologies	1	III	2014
	Solids Agglomeration Technologies	0	IV	?
Beneficiation Separation	Gaseous Separation Technologies	3	III	2017
	Liquid Separation Technologies	2	III	2017
	Granular Solids Physical Separation Technologies	1	III	2014
	Granular Solids Chemical Separation Technologies	1	III	2014
Separation and Internal Materials Handling	Granular materials performance models	0	III	2007
Internal Materials Handling	Liquid and Gas Containment Technologies	3	II	2009
	Continuous Materials Handling Technologies	2	II	2015
	Cyclic Materials Handling Technologies	3-7	III	2010
Site Planning, Monitoring	Mapping Technologies	1-7	III	2006
	Remote Geophysical Surveying Technologies	1-7	III	2005
	In Situ Geophysical Survey Technologies	1-7	III	2007
	Sample Analysis Technologies	1-7	III	2006
Site Planning, Monitoring, Site Reclamation	Field Sampling Technologies	1-7	II	2007
Transportation and Storage	Human&Robotic Transportation Technologies	7	III	2010
Anchoring	Soil Anchoring Technologies	3	III	2008
	Rock Anchoring Technologies	2	III	2009
Anchoring, Ground Stability Control, Site Reclamation	Granular materials performance models	0	III	2007
Ground Stability Control	Ground Stability Control Technologies	2	III	2012
Ground Stability Control, Monitoring	Ground Stability Monitoring	2	II	2012
Waste Management, Site Reclamation	Pit and Trench Excavation Technologies	1-7	III	2008
Monitoring	Process Monitoring Technologies	1-4	II	2012
Monitoring, Site Reclamation	Drilling Technologies	1-7	III	2007

Maturity Level – Technologies for 13.1 Resource Extraction

Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
Mapping Technologies Remote Geophysical Survey Technologies	Prospecting and Delineation, Site Planning, Monitoring	2-9 9	III III	2005 2005
Human & Robotic Transportation Technologies	all Resource Assessment capabilities, all Resource Acquisition capabilities, Transportation and Storage	5-9	III	2008
Pit and Trench Excavation Technologies	all Resource Assessment capabilities, Waste Management, Site Reclamation	2, 6-9	III	2005
Drilling Technologies	all Resource Assessment capabilities; Underground Liquids and Gases, Regolith, and Rock Resource Acquisition; Monitoring and Site Reclamation	2, 6-9	III	2005
In Situ Geophysical Survey Technologies	Prospecting, Delineation, Site Planning, Monitoring	6-9	III	2005
Field Sampling Technologies	Prospecting, Delineation, Site Planning, Monitoring, Site Reclamation	9	I	2006
Sample Analysis Technologies	Prospecting and Delineation, all Resource Beneficiation capabilities, Site Planning and Monitoring	9	III	2005
Dust Mitigation/ Control Technologies	Development, all Resource Acquisition capabilities, all Beneficiation capabilities, and Dust Control	1-5	IV	2007
Atmospheric Extraction Methods	Development, Atmospheric Gases Resource Acquisition	6	II	2015
Borehole Liquid & Gas Extraction Methods	Development, Underground Liquids and Gases Resource Acquisition	6	III	2019
Surface Extraction (Mining) Methods Underground Extraction (Mining) Methods	Development, Regolith and Rock Resource Acquisition	6 6	II II	2005 2025
In Situ Extraction Methods	Development, Mixed Materials Resource Acquisition	6	III	2007
Tunnel/Shaft Excavation Technologies	Development, Rock Resource Acquisition, Excavated Openings	6	III	2020
Gas Collection Technologies	Development; Atmospheric Gases, Underground Liquids and Gases Resource Acquisition	6	II	2011
Granular materials performance models	Development; Regolith and Rock Resource Acquisition, and Excavated Openings as Product; Beneficiation Separation and Internal Materials Handling; Site Management, Anchoring, Ground Stability Control, Site Reclamation	1-4	III	2005
Process Monitoring Technologies	all Resource Acquisition and Beneficiation capabilities	2-6	III	2007
Continuous Materials Handling Technologies Cyclic Materials Handling Technologies	all Resource Acquisition capabilities, and Beneficiation Internal Materials Handling	2, 6 6-9	II III	2020 2005
Liquid and Gas Containment Technologies	Atmospheric Gases, Underground Liquids and Gases Resource Acquisition, Internal Materials Handling	6	II	2005
Regolith & Rock Fragmentation Technologies Regolith & Rock Excavation Technologies Regolith & Rock Transport Technologies	Regolith and Rock Resource Acquisition, and Excavated Openings as Product	6 6 6	III III II	2005 2006 2005
Gas-Liquid Phase Change Technologies Solid-Gas Phase Change Technologies Solid-Liquid Phase Change Technologies Solid-Plasma Phase Change Technologies	Beneficiation Change of Phase	8 6-8 6-8 1, 8	II II II III	2010 2010 2010 ?
Solids Comminution Technologies Solids Agglomeration Technologies	Beneficiation Particle Size Change	1-6 1-6	III IV	2009 ?
Gaseous Separation Technologies Granular Solids Chemical Separation Technologies Granular Solids Physical Separation Liquid Separation Technologies	Beneficiation Separation	1-6 1-6 1-6 1-6	III III III III	2012 2009 2009 2012
Ground Stability Control Technologies Ground Stability Monitoring	Ground Stability Control Ground Stability Control, Monitoring	2, 6 6	III II	2007 2007
Soil & Rock Anchoring Technologies	Anchoring	2, 6	III	2005

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 flowrate).
    - 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
  - Collection and Purification of Lunar Propellant Resources, Technology Applications, Inc.

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

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Academia

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- Brad Blair, Colorado School of Mines

Description
13.2 Material Handling and Transportation

- 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.

13.2 Material Handling and Transportation

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 and Transportation CBS

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - Resource Extraction 13.1
  - Material Handling and Transportation_ 13.2
    - Fixed-Site Transportation 13.2.1
      - Carrier Concept 13.2.1.1
      - Operational Concept 13.2.1.2
    - Mobile Material Transportation 13.2.2
      - System Range 13.2.2.1
      - Carrier Concept 13.2.2.2
      - Operational Concept 13.2.2.3
      - Road Type 13.2.2.4
    - Payload Material Handling 13.2.3
      - Processing Maturity 13.2.3.1
      - Material Transport Container 13.2.3.2
      - Planetary Effects on Material Handling 13.2.3.3
    - Cross Platform Capabilities, Reliability and Logistics 13.2.4
      - Transport Power or Energy 13.2.4.1
      - System Capacity and Co-Scaling 13.2.4.2
      - Mechanism and Actuators 13.2.4.3
      - Sensing and Artificial Intelligence 13.2.4.4
      - Reliability and Logistics 13.2.4.5
  - 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 and Certification 13.6

Requirements /Assumptions
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

Team 13: In-Situ Resource Utilization

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

Capability	Products To Material Handling & Transportation
High-Energy Power & Propulsion 2	• Power to startup short and long distance transport and environmental control in shipping containers. • ISRU fuel compatible power/prop. sys.
In-Space Transportation 3	• Delivery of MH&T assets (infrastructure, parts and supplies.) • Delivery in space of ISRU products. • ISRU propellant compatible systems
Advanced Telescopes & Observatories 4	
Telecommunications and Navigation 5	• Vehicle location and navigation • Low bandwidth command and control
Robotic Access to Planetary Surfaces 6	• Pre-positioning of MH&T assets • ISRU fuel compatible power/prop. sys
Human Planetary and Landing Systems 7	• Pre-positioning of MH&T assets • ISRU fuel compatible power/prop. sys.
Human Health and Support Systems 8	• ISRU compatible air/water/solid reclamation/recycling systems

Capability Dependency

- Hi Criticality
- Med Criticality
- Lo Criticality

Material Handling and Transportation Commonality-Dependency With Other Capabilities

Products From Material Handling & Transportation	Capability	Products To Material Handling & Transportation
• Delivery and transfer of: • Propellants/oxidizer • Life support consumables and buffer gases • Fuel cell reagents • Logistics system	Human Exploration Systems and Mobility (9)	• Reconfigurable transportation platforms compatible with ISRU Ops. • ISRU fuel compatible power/prop. sys.
(same as above)	Autonomous Systems and Robotics (10)	• Autonomous and robotic systems for many aspects of MH&T. • ISRU fuel compatible power/prop. sys.
(same as above)	Transformational Spaceport and Range (11)	• Delivery of MH&T infrastructure, parts and supplies. • ISRU fuel compatible power/prop. sys.
• Mobility and in-situ data resource	Scientific Instruments and Sensors (12)	• Transportation hazard identification. • MH&T device status/integrity (pipes, roads, rail, augers, containers, etc.)
• Models, simulations, & engineering data of material behavior in low temperature/ pressure/ gravity • Logistics of terrestrial MH&T system operations	Advanced Modeling, Simulation, & Analysis (14)	• Model/simulate material behavior in low temperature/pressure/gravity (granular media, multiphase fluid, etc.) • Logistics of MH&T system operations
(same as above)	Systems Engineering Cost & Risk Analysis (15)	• Strategies for scaling up operation capability
	Nanotechnology and Advanced Concepts (16)	• 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

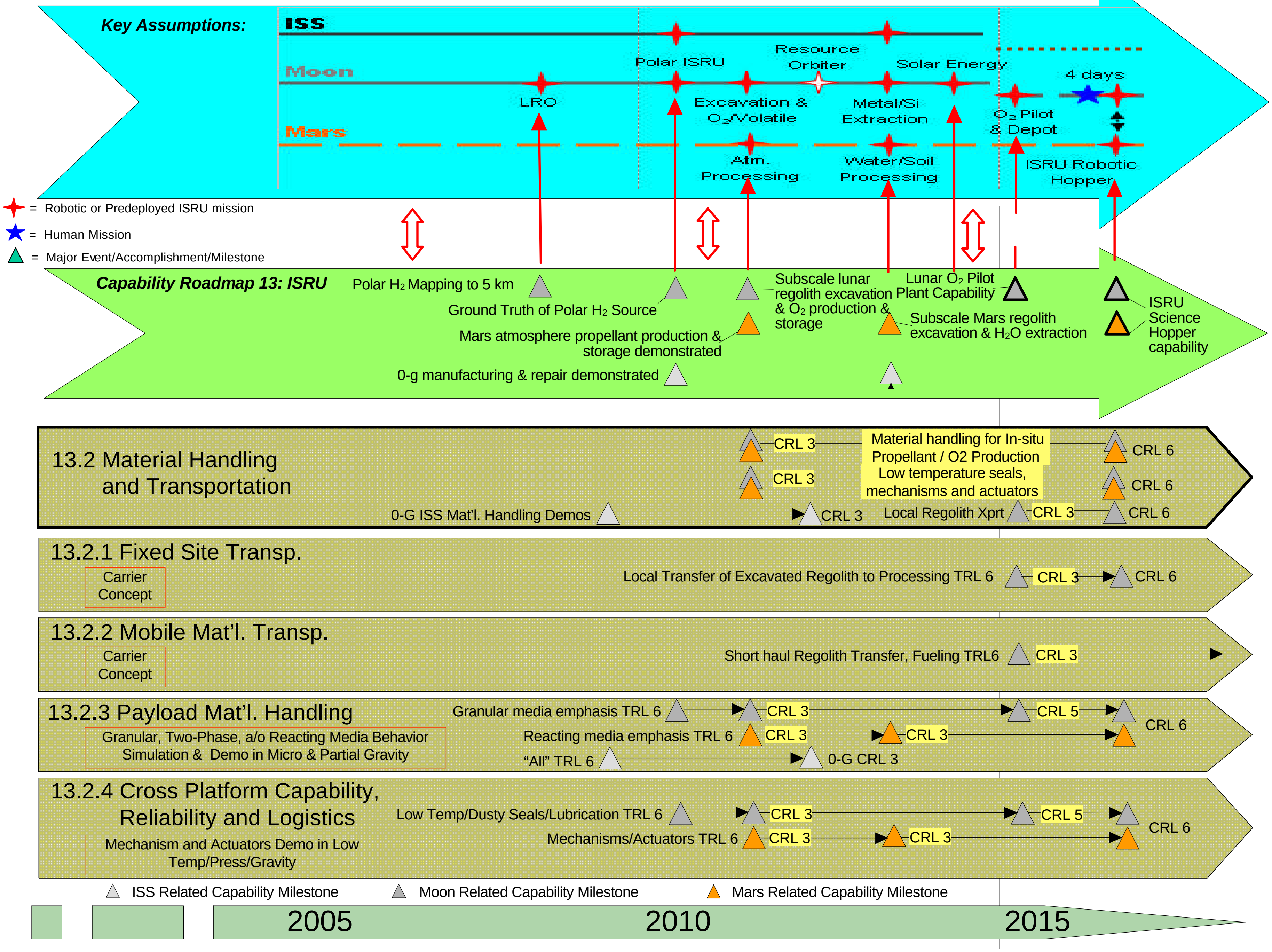
Surface Construction
- Delivery of Construction Feedstock

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

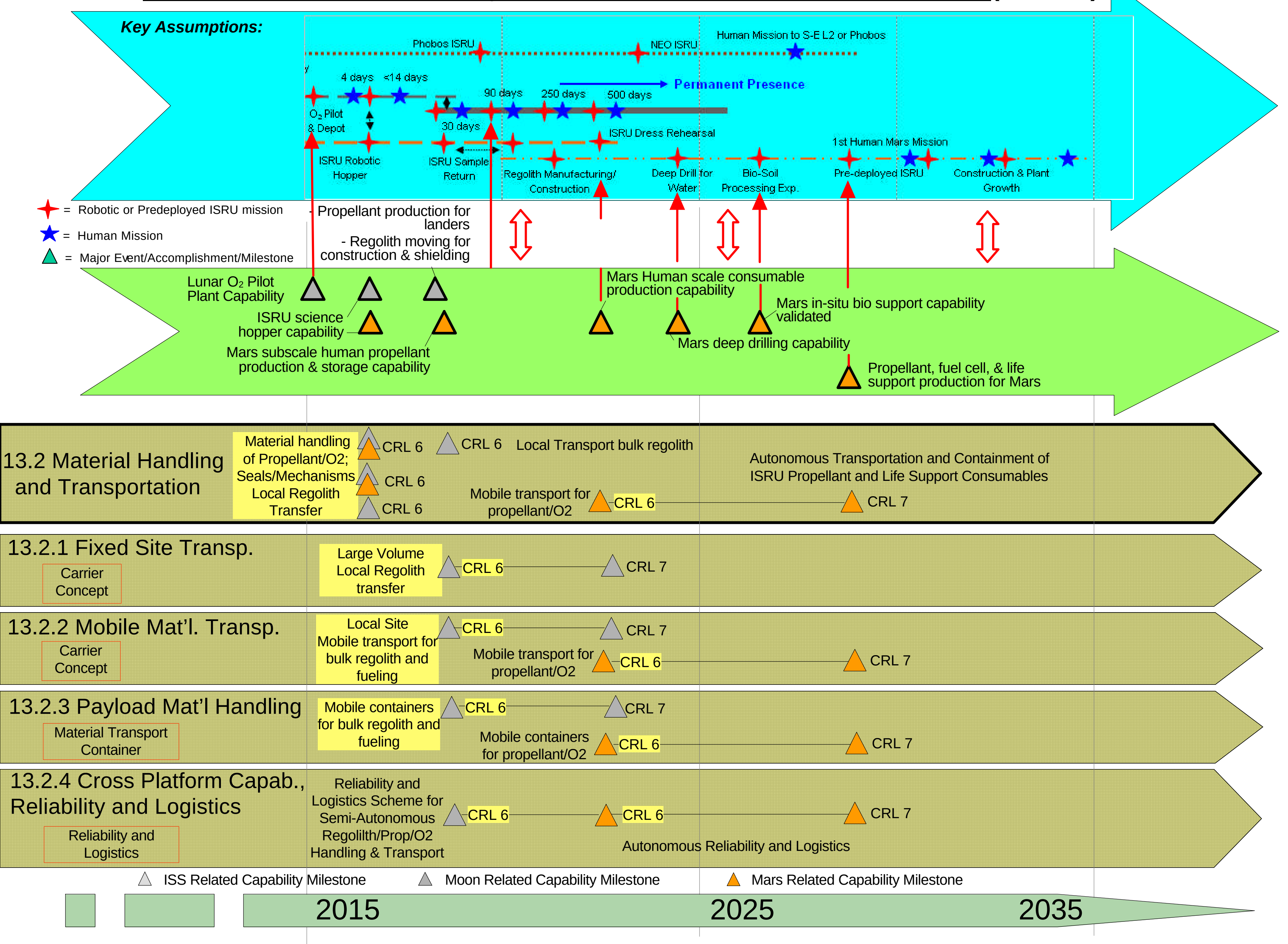
Unique Development and Certification
- Testing Requirements

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

13.2: (ISRU) Material Handling and Transportation Capability Roadmap (2005-16)



13.2: (ISRU) Material Handling and Transportation Capability Roadmap (2005-16)



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

Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
				CRL	R&D3	Need Date
13.2.1	Fixed-Site Transportation	13.2.1.1	Carrier Concept	0-1	III	2018
		13.2.1.2	Operational Concepts	0-1	III	2018
13.2.2	Mobile Material Transportation	13.2.2.1	System Range	0-1	II	2018
		13.2.2.2	Carrier Concept	0-1	III	2018
		13.2.2.3	Operational Concepts	0-1	III	2018
		13.2.2.4	Road Types	0-1	II	2018
13.2.3	Payload Material Handling	13.2.3.1	Processing Maturity	0-1	II	2012 - 2018
		13.2.3.2	Material Transport Containers	0-1	III	2016
		13.2.3.3	"Planetary" Effects on Material Handling	0-1	IV	2012
13.2.4	Cross Platform Capabilities, Reliability, Logistics	13.2.4.1	Transportation Power or Energy	0-1	II	2016
		13.2.4.2	System Capacity and Co-Scaling	0-1	II	2018
		13.2.4.3	Mechanisms and Actuators	0-1	IV	2012
		13.2.4.4	Sensing and Artificial Intelligence	0-1	III	2012 2018
		13.2.4.5	Reliability and Logistics	0-1	II	2018

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
					CRL	R&D3	Need Date
Fixed-Site Transportation	13.2.1.1	Carrier Concept	13.2.1.1.1	Conveyers	0-1	III	2018
			13.2.1.1.2	Augers	0-1	III	2018
			13.2.1.1.3	Pipes/Plumbing/Pumps	1	III	2014
			13.2.1.1.4	Crane	0-1	III	2018
	13.2.1.2	Operational Concepts	13.2.1.2.1	Human directed, in situ	0-1	III	2024
			13.2.1.2.2	Human directed, remote	0-1	III	2016
			13.2.1.2.3	Semi-autonomous	0-1	III	2024
			13.2.1.2.4	Fully autonomous	0-1	III	2024
Mobile Material Transportation	13.2.2.1	System Range	13.2.2.1.1	Planetary (pole to equator)	0-1	IV	>2030
			13.2.2.1.2	Site (20 km)	0-1	III	2018
			13.2.2.1.3	Plant (200 m)	0-1	III	2018
			13.2.2.1.4	Short-Haul (20 m)	0-1	II	2016
	13.2.2.2	Carrier Concept	13.2.2.2.1	Surface Vehicles	0-1	III	2024
			13.2.2.2.2	Flight Vehicles	0-1	IV	2030
	13.2.2.3	Operational Concepts	13.2.2.3.1	Human directed in situ	0-1	III	2024
			13.2.2.3.2	Human directed, remote	0-1	III	2024
			13.2.2.3.3	Semi-autonomous	0-1	III	2024
			13.2.2.3.4	Fully-autonomous	0-1	III	2024
	13.2.2.4	Road Types	13.2.2.4.1	Unimproved Terrain	0-1	II	2018
			13.2.2.4.2	Improved Road	0-1	III	2024

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
					CRL	R&D3	Need Date
Payload Material Handling	13.2.3.1	Processing Maturity	13.2.3.1.1	Raw Resource	0-1	II	2018
			13.2.3.1.2	Beneficiated Resource	0-1	II	2018
			13.2.3.1.3	Processed Consumable or Feedstock	0-1	II	2018
			13.2.3.1.4	Finished Products	0-1	II	2024
			13.2.3.1.5	Waste or Recyclable Material	0-1	II	2024
	13.2.3.2	Material Transport Containers	13.2.3.2.1	Open to environment	0-1	III	2018
			13.2.3.2.2	Enclosed/sealed	0-1	III	2018
	13.2.3.3	"Planetary" Effects on Material Handling	13.2.3.3.1	Gravitational Buoyancy	0-1	IV	2012
			13.2.3.3.2	Flow and stability of granular media	0-1	IV	2012
			13.2.3.3.3	Material properties in extreme environments	0-1	IV	2012

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment CRL	R&D3	Need Date
Cross Platform Capabilities, Reliability, Logistics	13.2.4.1	Transportation Power or Energy	13.2.4.1.1	Power or Energy Loads	1	II	2012
			13.2.4.1.2	Power or Energy Sources	1	III	2012
			13.2.4.1.3	Waste Power or Energy	0-1	III	2024
			13.2.4.1.4	Duty Cycle	0-1	II	2016
	13.2.4.2	System Capacity and Co-Scaling	13.2.4.2.1	Capacity Growth with other Sub Elements	0-1	II	2016
			13.2.4.2.2	Scale-Up Extrapolations	0-1	IV	2016 2024
	13.2.4.3	Mechanisms and Actuators	13.2.4.3.1	Prime movers, motors, pumps	0-1	III	2014
			13.2.4.3.2	Material or container loading and unloading	0-1	II	2018
			13.2.4.3.3	Wheels, tracks, conveyors, cranes	0-1	III	2018
			13.2.4.3.4	Steering	0-1	III	2024
			13.2.4.3.5	Seals	0-1	IV	2012
			13.2.4.3.6	Lubrication	0-1	IV	2012
	13.2.4.4	Sensing and Artificial Intelligence	13.2.4.4.1	State Sensing	0-1	III	2012 2024
			13.2.4.4.2	Artificial Intelligence and Autonomy	0-1	IV	2024
	13.2.4.5	Reliability and Logistics	13.2.4.5.1	Dust related issues	0-1	IV	2016
			13.2.4.5.2	Mechanical cycling	0-1	II	2016
			13.2.4.5.3	Seals	0-1	II	2016
			13.2.4.5.4	Overloading	0-1	II	2016
			13.2.4.5.5	Vehicle mass versus durability	0-1	II	2016
			13.2.4.5.6	Payload Material/Product Flow Logistics	0-1	III	2016
			13.2.4.5.7	Fueling Logistics	0-1	II	2016
			13.2.4.5.8	Maintenance and Repair strategy	0-1	IV	2016

Metrics
13.2 Material Handling and Transportation

- 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

Funding in Place
13.2 Material Handling and Transportation

- 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.

Gaps, Risks and Strategies
13.2 Material Handling and Transportation

- 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

Resource Processing Roadmap Team

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- 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 <u>2250 kg of Water This Year</u> 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

- **In-Situ Resource Utilization** 13.0
  - **Resource Processing** 13.3
    - 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

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - Resource Processing 13.3
    - Mission Consumable Protection 13.3.1
      - 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 13.3.1.1.3
        - Molten Salt Electrolytic Reduction of Regolith 13.3.1.1.4
        - Hydrogen Extraction 13.3.1.1.5
        - Carbochlorination Reduction of Regolith 13.3.1.1.6
        - Hydrofluoric Acid Leach 13.3.1.1.7
        - Water Electrolysis 13.3.1.1.8
        - Solid Oxide CO2 Electrolysis 13.3.1.1.9
        - Ionic Liquid CO2 Electrolysis 13.3.1.1.10
        - 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
    - Feedstock Production for In-Situ Manufacturing 13.3.2
    - Feedstock Production for Surface Construction 13.3.3

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	Capability	Capability Products To Resource Processing
• Propellant production • Fuel Cell Reagents	High-Energy Power & Propulsion (2)	• Solar & nuclear power to support power-intensive ISRU activities
• Propellant production and pressurant/purge gases for lander reuse and in-space depots	In-Space Transportation (3)	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Gases for Inflatable Structures	Advanced Telescopes & Observatories (4)	
• 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	Robotic Access to Planetary Surfaces (6)	• Pre-positioning & activation of ISRU assets
• Materials for Landing pads/plume debris shielding • Propellant production for lander reuse	Human Planetary Landing Systems (7)	• Delivery of ISRU capabilities to sites of exploration

Resource Processing Interdependency with other Capabilities

Products From Resource Processing	Capability	Capability Products To Resource Processing
• Gases for inflation & buffer gases • Life support consumable production for backup • Fertilizer for plant growth • Materials for in-situ manufacturing	Human Health and Support Systems (8)	• Carbon-based waste products as resource for ISRU
• O_2 production for EVA & Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Propellants & fuel cell reactants for surface vehicles	Autonomous Systems & Robotics (10)	• ISRU Compatable Robots/rovers Software & FD&R logic for autonomous operation
	Scientific Instruments & Sensors (12)	• Resource location & characterization information • Self Calibrating or Extended Calibration Life Sensors
	Nano-Technology (16)	• Nanotube catalysts for Microchemical Reactors

Resource Processing Interdependency with other ISRU Elements

Team 13: In-Situ Resource Utilization

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 mobility systems for Resource Processing "Waste" removal.

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

Consumables

Manufacturing Feedstock

Construction Feedstock

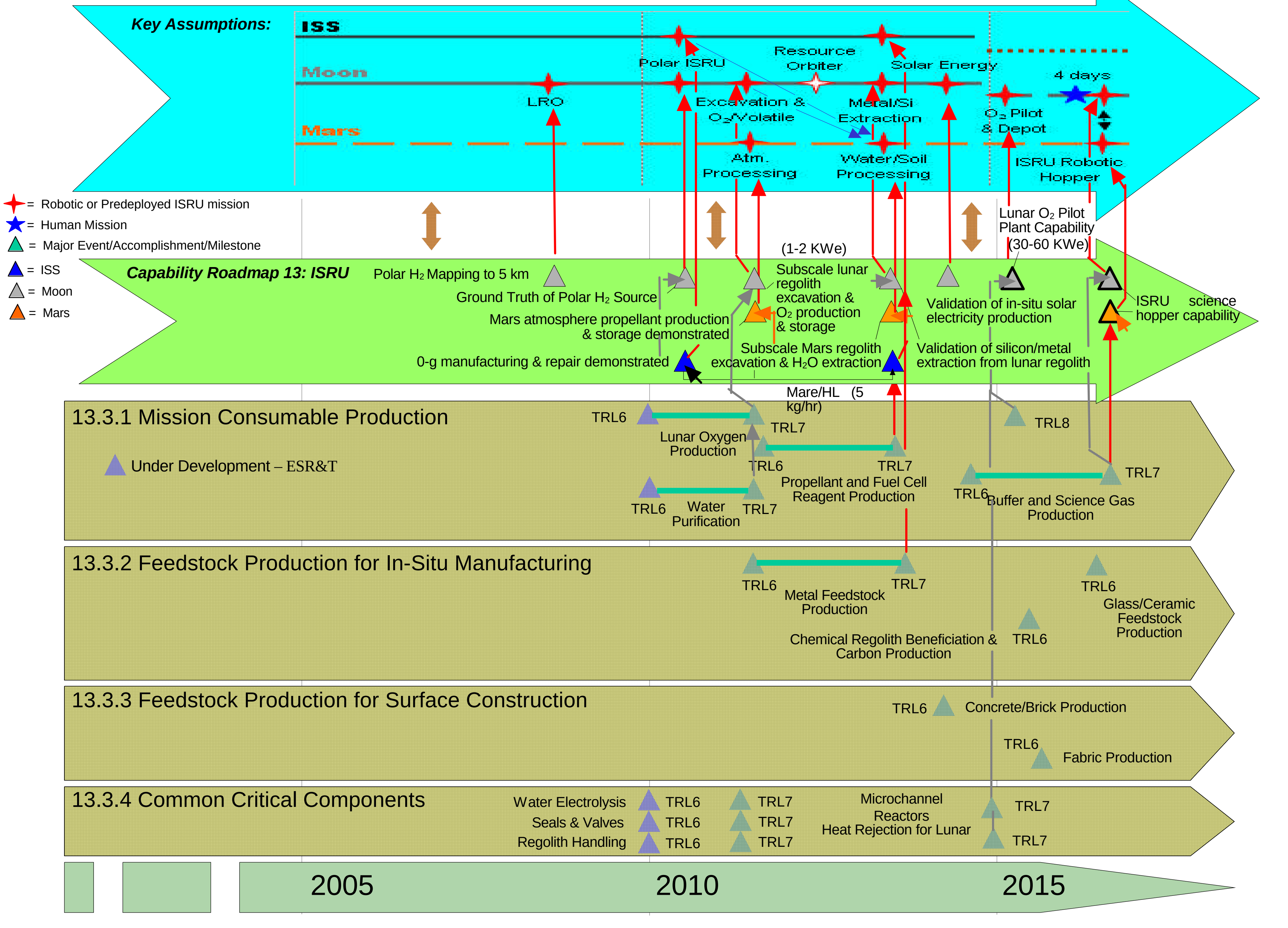
Products From Resource Processing

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

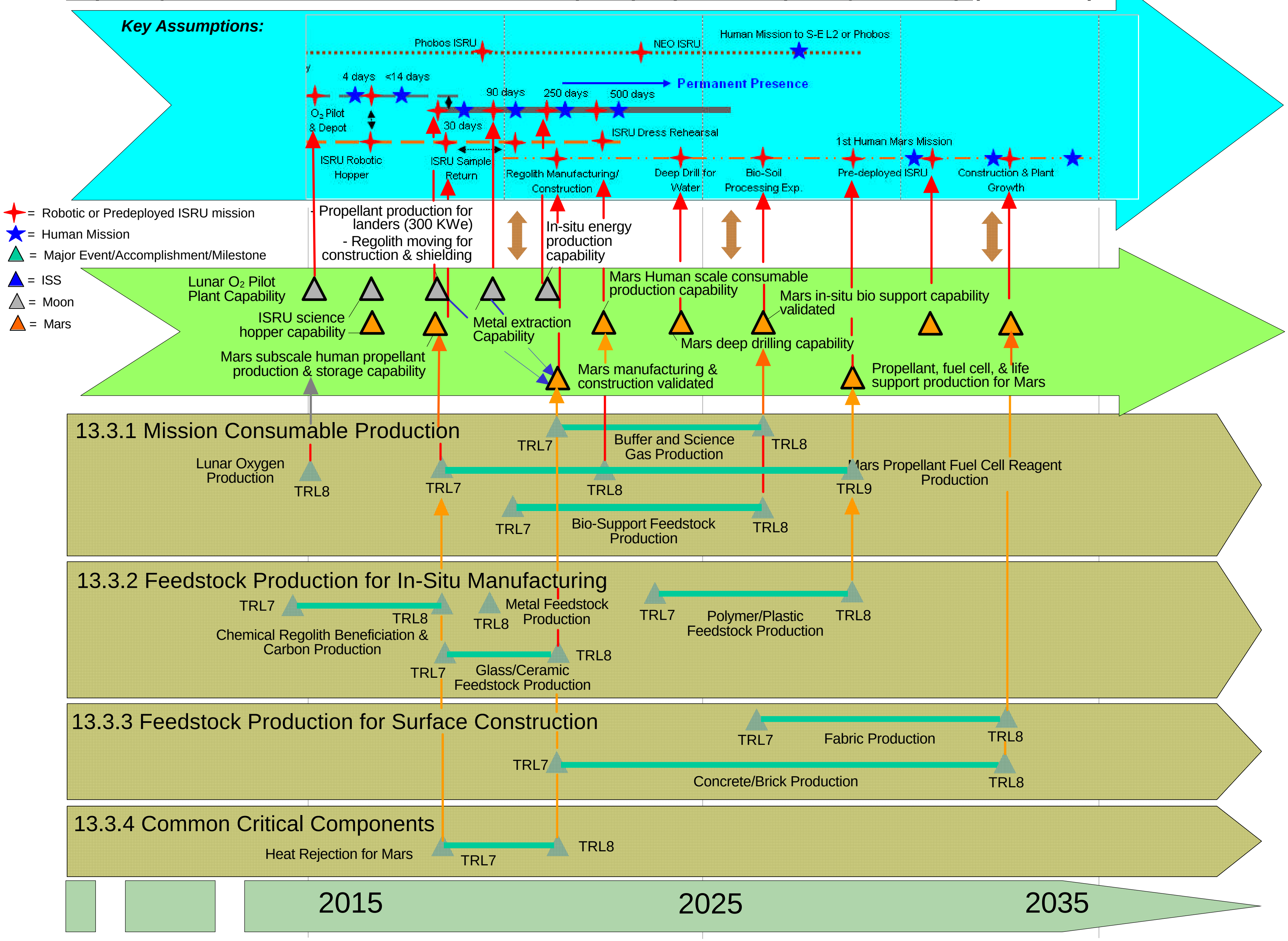
Surface Manufacturing w/ In-Situ
- Iron, Carbon Steel, Titanium & Aluminum for Manufacturing
- Carbon
- Plastics for Parts Manufacture
- Silicon for Electronics and Photovoltaic Arrays
- Glass for PV arrays

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

Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2005 to 16)



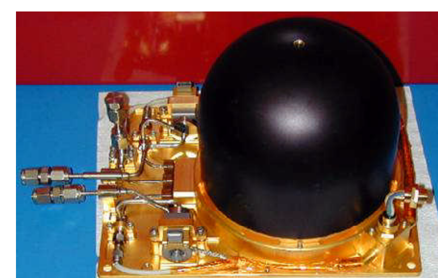
Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2015 to 35)



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

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assesment		
		CRL	R&D3	Need Date
Mission Consumables Production	*Oxygen Production*	3	*Mars I, Moon III*	Mars & Moon 2012
	Methane Production	3	*Mars I, Moon IV*	Mars 2012, Moon 2016
	Hydrogen Production	3	*Mars I, Moon III*	2016
	Powdered Metals for Propulsion	1	*IV*	2016
	Ethylene Production	2	*II*	Mars 2012, Moon 2016
	Methanol Production	2	*I*	Mars 2012, Moon 2016
	Carbon Monoxide Production	3	*I*	Mars 2012, Moon 2020
	Ammonia Production	1	*II*	Mars 2020 ?
	Water Purification	3	*I*	2014
	Nitrogen Production	3	*Mars I, Moon IV*	Mars 2012, Moon 2016
	Argon Production	3	*Mars I, Moon IV*	Mars 2012, Moon N/A
	Fertilizer Production	1	*Mars II, Moon III*	Mars 2020
Feedstock for Manufacturing	Carbon Production	2	*II*	Mars
	Iron & Iron Alloys	1-2	*III*	Moon 2014, Mars 2020
	Titanium Alloys	2	*III*	Moon 2014, Mars 2020
	Aluminum Alloys	2	*III*	Moon 2014, Mars 2020
	Silicon	3	*III*	Moon 2014, Mars 2020
	Glass	2	*I*	Moon 2014, Mars 2020
	Ceramics	2	*I*	Moon 2014, Mars 2020
	Plastics	1	*V*	2020?

Maturity Level – Capabilities for Resource Processing

Capability	**Key Technologies or Sub-Capabilities**	**Capability Readiness Assesment**		
		CRL	R&D3	Need Date
Feedstock for Construction	Concrete	2	*II*	Moon 2020
	Slag	2	*I*	2014
	Fabric	2	*II*	2020
Common Critical Components	Reaction Chamber Seals for High Vacuum, Dusty Environments	1	*III*	2012
	Product Shaping (Ingots, Bar Stock, Powdered Metal	1	*III*	2014
	High Efficiency Gas Separation	3	*III*	2012
	Hydrogen Drying	1	*I*	2016
	Oxygen Purification	1	*I*	2016

Maturity Level – Technologies Resource Processing

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Hydrogen Reduction of ilmenite	*Oxygen Production, Iron Production*	*Oxygen 4, Iron 3*	*Oxygen II, Iron III*	*O2 2012, Iron 2014*
Carbothermal Reduction of	*Oxygen Production, Iron Production*	*Oxygen 4, Iron 3*	*Oxygen II, Iron III*	*O2 2012, Iron 2014*
Molten Regolith Electrolysis	*Oxygen & Metal Production*	*2*	*V*	*O2 2012, Metal 2014*
Molten Salt Electrolytic Reduction of Regolith	*Oxygen, Iron, Aluminum, Titanium, Silicon Production*	*4*	*II*	*O2 2012, Metal 2014*
Carbochlorination reduction of anorthite and ilmenite	*Oxygen Production*	*2*	*IV*	*2012*
Hydrofloric Acid Leach	*Oxygen Iron, Silicon, Aluminum, Titanium & Glass Production*	*3*	*III*	*O2 2012, Metal 2014*
Solid Oxide CO2 Electrolysis	*Oxygen & Carbon Monoxide Production*	*4*	*III*	*2012*
Ionic Liquid CO2 Electrolysis	*Oxygen, Carbon Monoxide & Carbon Production*	*1*	*IV*	*2012*
Molten Carbonate CO2 Electrolysis	*Oxygen, Carbon Monoxide & Carbon Production*	*3*	*IV*	*2012*
Cold Plasma CO2 Disassociation	*Oxygen, Carbon Monoxide Production*	*3*	*II*	*2012*
Sabatier Reactor	*Oxygen & Methane Production*	*5*	*I*	*2012*
Reverse Water Gas Shift	*Oxygen, Water & Carbon Monoxide Production*	*4*	*II*	*2012*
Hydrocarbon Reformer	*Hydrogen Production*	*4*	*I*	*2012*
Liquid Water Electrolysis	*Oxygen Production*	*9*	*I*	*2012*
Gas Phase H20 Electrolysis	*Oxygen Production*	*5*	*II*	*2012*
Methanol Reactor	*Methanol Production*	*4*	*II*	*2012*
Fischer-Tropsch Reator	*Ethylene & Plastics Production*	*3*	*IV*	*Ethylene 2012, Plastics 2030*

Maturity Level – Technologies Resource Processing

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Haber Process	*Ammonia Production*	*4*	*II*	*2025*
Particulate Removal	*Water Purification*	*9*	*I*	*2015*
Deionization Bed	*Water Purification*	*9*	*I*	*2015*
Electrodialysis (Deionization)	*Water Purification*	*6*	*I*	*2015*
Distillation	*Water Purification*	*9*	*I*	*2015*
Hydrate Adsorption/Desorption	*Water Purification*	*7*	*I*	*2015*
Reverse Osmosis	*Water Purification*	*6*	*I*	*2015*
Ammonia Decomposition	*Nitrogen/Hydrogen Production*	*4*	*II*	*201*
Gas Separation Membranes	*Nitrogen, Argon & Carbon Monoxide Production*	*4*	*III*	*2012*
Cryogenic Gas Separation	*Nitrogen, Argon & Carbon Dioxide Production*	*4*	*II*	*2012*
Adsorption Gas Separation	*Nitrogen, Argon & Carbon Dioxide Production*	*4*	*II*	*2012*
Ammonia-based Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Urea-based Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Oxides of Nitrogen Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Potassium-based	*Fertilizer Production*	*2*	*III*	*2025*
Phosphorus-based	*Fertilizer Production*	*2*	*III*	*2025*
Catalytic Decomposition of CO	*Carbon Production*	*2*	*III*	*2025*
Hydrochloric Acid Leach	*Iron, Aluminum, Silicon, Glass*	*4*	*II*	*2014*

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

Capability Development Strategy

- 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 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 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

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External: Edward D. McCullough, Boeing

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- 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
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- Marvin E. Criswell, Colorado State University
- Mike Gaffey, Space Studies Department University of North Dakota

Capability 13.4: Surface Manufacturing with In Situ Resources

- 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.

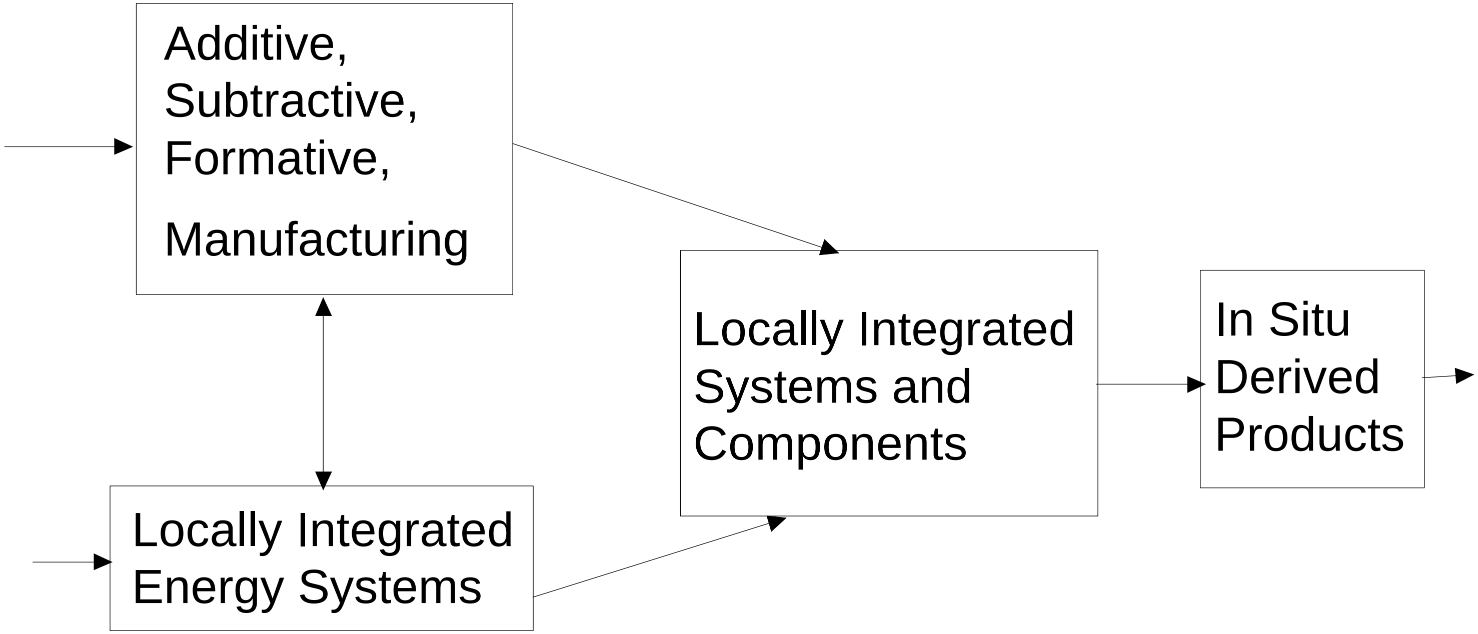
Benefits of Manufacturing with In Situ Resources

- 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 w/ In-Situ Resources

- In-Situ Resource Utilization 13.0
  - **Surface Manufacturing with In-Situ Resources** 13.4
    - **Additive Manufacturing Techniques** 13.4.1
      - Free Form Fabrication 13.4.1.1
      - Composite Lay up 13.4.1.2
      - Chemical Vapor Deposition 13.4.1.3
      - Combustion Synthesis 13.4.1.4
    - **Subtractive Manufacturing Techniques** 13.4.2
      - Machining 13.4.2.1
      - E-beam/Laser Cutting & Ablation 13.4.2.2
    - **Formative Manufacturing Techniques** 13.4.3
      - Tape Casting 13.4.4.1
      - Powder Casting 13.4.4.2
      - Casting 13.4.4.3
      - Extrusion 13.4.4.4
      - Sintering 13.4.4.5
    - **Locally Integrated Energy Systems** 13.4.4
      - Photovoltaic Cell/Array Production 13.4.5.1
      - Solar Collector/ Concentrator Production 13.4.5.2
      - Rectenna/Power Beaming Production 13.4.5.3
      - Thermal Storage Media & System Construction 13.4.5.4
      - Battery Material/ Assembly Construction 13.4.5.5
    - **Locally Integrated Systems & Components** 13.4.5
      - Precision Assembly Capability 13.4.6.1
      - Geometric Situational Awareness 13.4.6.2
      - Precision Machining 13.4.6.3
      - Precision Joining/ Fastening 13.4.6.4
      - Precision Component Organization & Handling 13.4.6.5
    - **Manufacturing Support Systems** 13.4.6
      - Non Destructive Evaluation (NDE) 13.4.6.1
      - Metrology 13.4.6.2

Surface Manufacturing with In Situ Resources



Resource Processing Interdependency with other Capabilities

Team 13: In-Situ Resource Utilization

Products From Surface Mfg & Resources	Capability	Capability Products To
• Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication	High-Energy Power & Propulsion	• Solar & nuclear power to support power-intensive ISRU activities
• Parts and components for Lunar infrastructure	In-Space Transportation	
• Repair/replacement of reflector coatings • Shaping crater for collector • Power availability from ISRU fabricated solar cells	Advanced Telescopes & Observatories	
• Power beaming for power to robots	Robotic Access to Planetary Surfaces	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Repair, replace and fabricate system components	Human Planetary Landing Systems	• Precision landing • Delivery of ISRU capabilities to sites of exploration
• Energy rich environment from ISRU fabricated solar cells • Materials for in-situ manufacturing	Human Health and Support Systems	• Carbon-based waste products as resource for ISRU
• Spare parts produced on demand for mobility systems	Human Exploration Systems & Mobility	• Crew/robotics/rovers to perform ISRU surface activities
• Energy rich environment from ISRU fabricated solar cells • Power beaming for power to robots	Autonomous Systems & Robotics	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Energy rich environment from ISRU fabricated solar cells	Scientific Instruments & Sensors	• Resource location & characterization information

ISRU Commonality-Dependency With ISRU Elements (13.4.1,2&3)

ISRU Element Products To Surface Manufacturing

- **Resource Transportation**
- Surface mobility systems platforms for Raw Resource Transportation to In Situ Manufacturing
- Surface mobility systems for Resource Processing "Waste" removal.
- 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)

Team 13: In-Situ Resource Utilization

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
- Surface mobility systems for Resource Processing “Waste” removal.

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

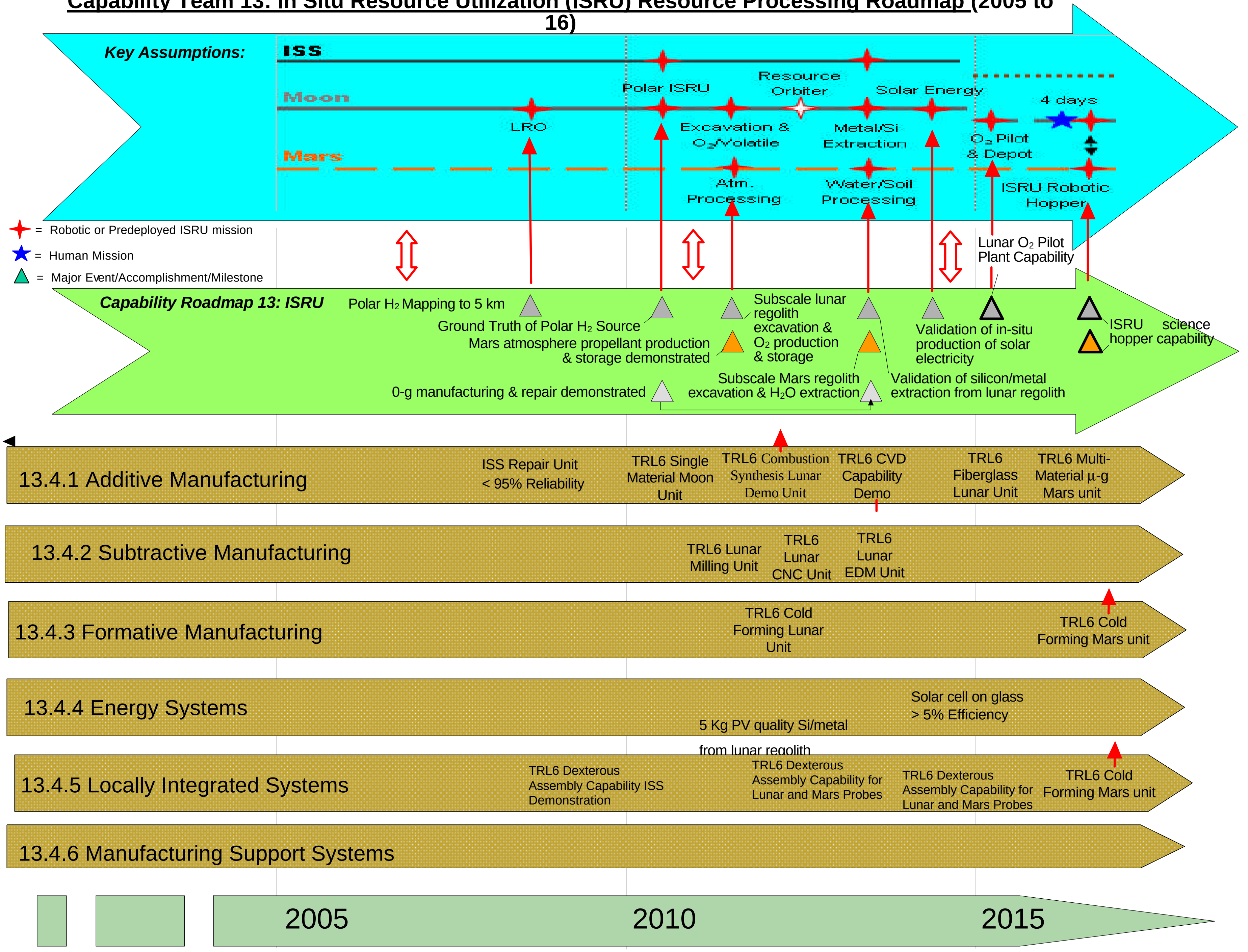
Power Beaming/ Thermal Storage

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

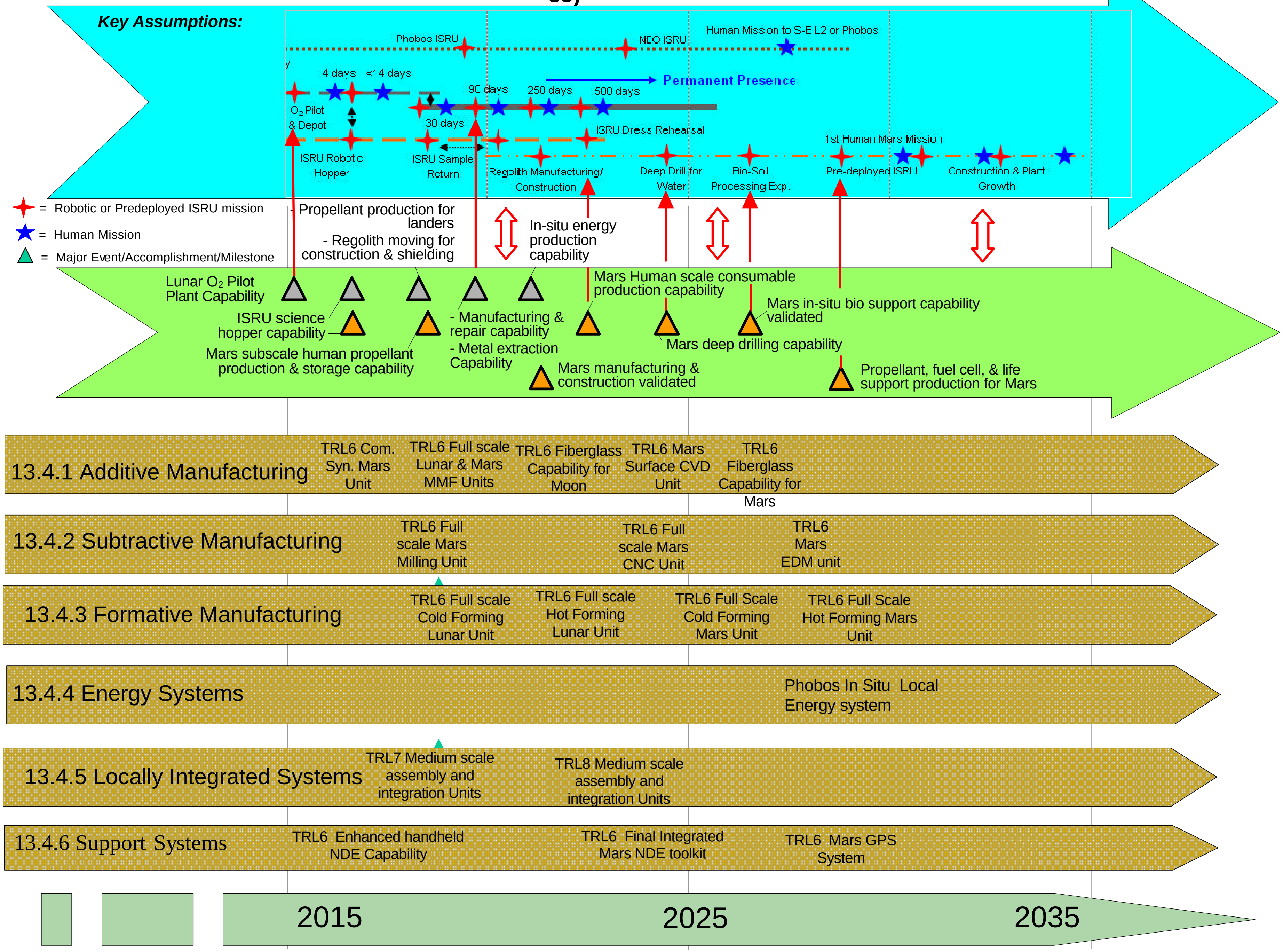
Product Storage & Distribution
- Energy for Life Support
- Energy for Propulsion
- Energy for charging for Fuel Cells
- Energy for Excavation
- Energy for Processing
- Energy for Construction

Surface Construction
- Energy for construction
- Energy for Excavation
- Energy for processing

Capability Team 13: In Situ Resource Utilization (ISRU) Resource Processing Roadmap (2005 to 16)

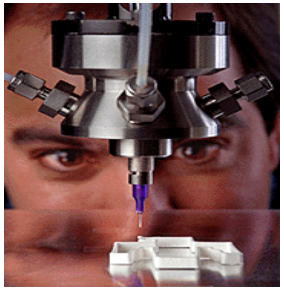


Capability Team 13: In Situ Resource Utilization (ISRU) Resource Processing Roadmap (2015 to 35)



Current State-of-the-Art for Surface Manufacturing with In Situ Resources

- Lunar Manufacturing with In 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.



Maturity Level – Capabilities
Surface Manufacturing with In Situ Resouces

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
13.4.1 Additive Manufacturing	Solid Free-form Fabrication (SFF)	2	II	2006
	Chemical Vapor Deposition (CVD)	2	II	2015
	Fiberglass Fabrication	3	II	2015
	Combustion Synthesis	2	II	2015
13.4.2 Subtractive Manufacturing	Milling	2	II	2008
	CNC Lathe and CNC Turning	2	II	2009
	Electrical Discharge Machining (EDM)	2	II	2011
13.4.3 Formative Manufacturing	Cold Forming	2	II	2008
	Hot Forming	2	II	2015
13.4.4 Locally Integrated Energy Systems	Photovoltaic Cell/Array Production	3	II	2010
	Solar Collector/Concentrator Production	2	II	2020
	Power Beaming Construction	3	II	2030
13.4.5 Locally Integrated Systems & Components	Precision Assembly	3	III	2008
	Precision Machining	3	III	2008
	Precision Joining/Fastening	3	III	2015
	Precision Component Organization & Handling	3	III	2015
13.4.6 Manufacturing Support Systems	Non-Destructive Evaluation (NDE)	1	II	2012
	Metrology	1	II	2015

Maturity Level – Technologies
Surface Manufacturing with In Situ Resources

Capability	Key Technologies or Sub-Capabilities	Technology Readiness Assessment		
		TRL	R&D3	Need Date
13.4.1 Additive Manufacturing	Solid Free-form Fabrication (SFF)	4	II	2006
	Chemical Vapor Deposition (CVD)	2	II	2015
	Fiberglass Fabrication	2	II	2015
	Combustion Synthesis	4	II	2015
13.4.2 Subtractive Manufacturing	Milling	2	II	2008
	CNC Lathe and CNC Turning	2	II	2009
	Electrical Discharge Machining (EDM)	2	III	2011
13.4.3 Formative Manufacturing	Cold Forming	2	II	2008
	Hot Forming	2	II	2015
13.4.4 Locally Integrated Energy Systems	Photovoltaic Cell/Array Production	3	II	2010
	Solar Collector/Concentrator Production	2	II	2009
	Power Beaming Construction	3	II	2011
13.4.5 Locally Integrated Systems & Components	Precision Assembly	4	III	2008
	Precision Machining	4	II	2008
	Precision Joining/Fastening	4	II	2011
	Precision Component Organization & Handling	4	II	2015
13.4.6 Manufacturing Support Systems	Non-Destructive Evaluation (NDE)	1	II	2012
	Metrology	1	II	2015

Metrics for Surface Manufacturing with In Situ Resources

- 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

Technology Gaps for Surface Manufacturing with In Situ Resources

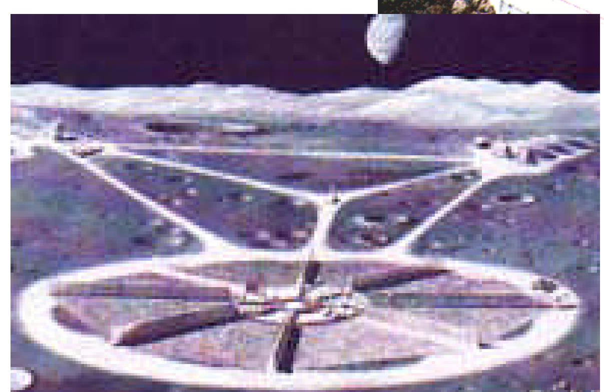
- Reduction of System Mass, for seed Manufacturing units.
- Although the systems will be human in-the-loop a maximum of autonomous and tele-operations must be developed
- Systems require the development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment.
- 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



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

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - **Surface Construction** 13.5
    - **Site Planning** 13.5.1
      - Site Survey & Characterization 1.5.1.1
      - Architectural Layout & Master Planning 13.5.1.2
      - Civil Engineering Design 13.5.1.3
      - Geospatial Information System (GIS) Configuration Control Tool 13.5.1.4
    - **Surface & Subsurface Preparation** 13.5.2
      - Road Construction 13.5.2.1
      - Foundation Construction 13.5.2.2
      - Utilidor Construction 13.5.2.3
      - Terrain Shaping, Grading & Rock Clearing 13.5.2.4
      - Underground Structures 13.5.3.5
      - Soil Stabilization (Mars Dust) 13.5.3.6
    - **Structure & Habitat Fabrication** 13.5.3
      - Construction Techniques & Methods 13.5.3.1
      - In Situ Building Materials 13.5.3.2
      - Access & Handling Equipment 13.5.3.3
      - In Situ Robotic / Human Construction Equipment 13.5.3.4
    - **Radiation & Micro Meteoroid Debris Shielding** 13.5.4
      - Radiation Shelters 13.5.4.1
      - Shields for Nuclear Reactors 13.5.4.2
      - Micrometeoroid Shielding 13.5.4.3
    - **Structure & Site Maintenance** 13.5.5
      - Integrity & Preventative Maintenance 13.5.5.1
      - Waste Management 13.5.5.2
      - Facility Management 13.5.5.3
    - **Landing & Launch Site** 13.5.6
      - Landing/Launch Pads 13.5.6.1
      - Plume Debris Shielding 13.5.6.2
      - Exhaust Flame Management 13.5.6.4
      - Sheltered Propellant and Consumables Farms 13.5.6.5
      - Mars Lightning Protection 13.5.6.6

Surface Construction Interdependency with other Roadmaps

Construction Products To Other Capabilities	Roadmap	Capability Products To Construction
• Radiation shields for nuclear reactors • Power Cable Deployment • Power distribution layout	High-Energy Power & Propulsion (2)	• Solar & nuclear power to support power-intensive ISRU activities
• Landing/Launch Pads • Surface Support Infrastructure	In-Space Transportation (3)	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Shaping crater • In-situ construction and fabrication • Foundation design & preparation	Advanced Telescopes & Observatories (4)	
• Landing pads/plume debris shielding • Landing Site Characterization/Preparation	Robotic Access to Planetary Surfaces (6)	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Landing pads/plume debris shielding • Landing Site Characterization/Preparation	Human Planetary Landing Systems (7)	• Precision landing • Delivery of ISRU capabilities to sites of exploration
• Habitat/shelter fabrication • Radiation shields from in-situ material • Micro Meteoroid Debris Shielding	Human Health and Support Systems (8)	
• Soil stabilization/dust control • Roadway infrastructures • Engineering properties of regolith	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Roadway infrastructures • Construction End Effectors and attachments	Autonomous Systems & Robotics (10)	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Geospatial Information System (GIS) • Data fusion of regolith characteristics • Engineering properties of regolith	Scientific Instruments & Sensors (12)	• Instrumentation for resource location & characterization information

Surface Construction Interdependency with other ISRU Elements

ISRU Element Products To

Resource Processing
- Ceramics for Construction Materials Fab (e.g. Bricks)
- Iron, Aluminum, and Steel for Structure & Habitat Fabrication
- Fiberglass for Composite Construction Materials
- Slag for Bricks
- Slag for Habitat Radiation Protection
- Slag for Nuclear Reactor Shielding

Resource Extraction
- Regolith Excavation & Physical Beneficiation

Resource Transportation
- Surface mobility systems platforms for Raw Construction Resources
- Surface mobility systems for Finished Product Utilization
- Surface mobility systems for Resource Processing "Waste" removal.

Surface Manufacturing w/In-Situ Resources
- Spare Parts for Surface Construction Systems
- Manufactured parts for Structure fabrication

Product Storage & Distribution
- Stored Gases/Liquids as inputs to Surface Construction

Surface Construction

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

Products From Surface Construction

Site Planning →

All
- General site planning and characterization

Surface & Subsurface Preparation →

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

Structure & Habitat Fabrication →

All
- Single and multifunctional structures

Radiation & Micro Meteoroid Debris Shielding →

All
- Radiation shielding for crew/equipment

Structure & Site Maintenance →

All
- General site & primary structure maintenance

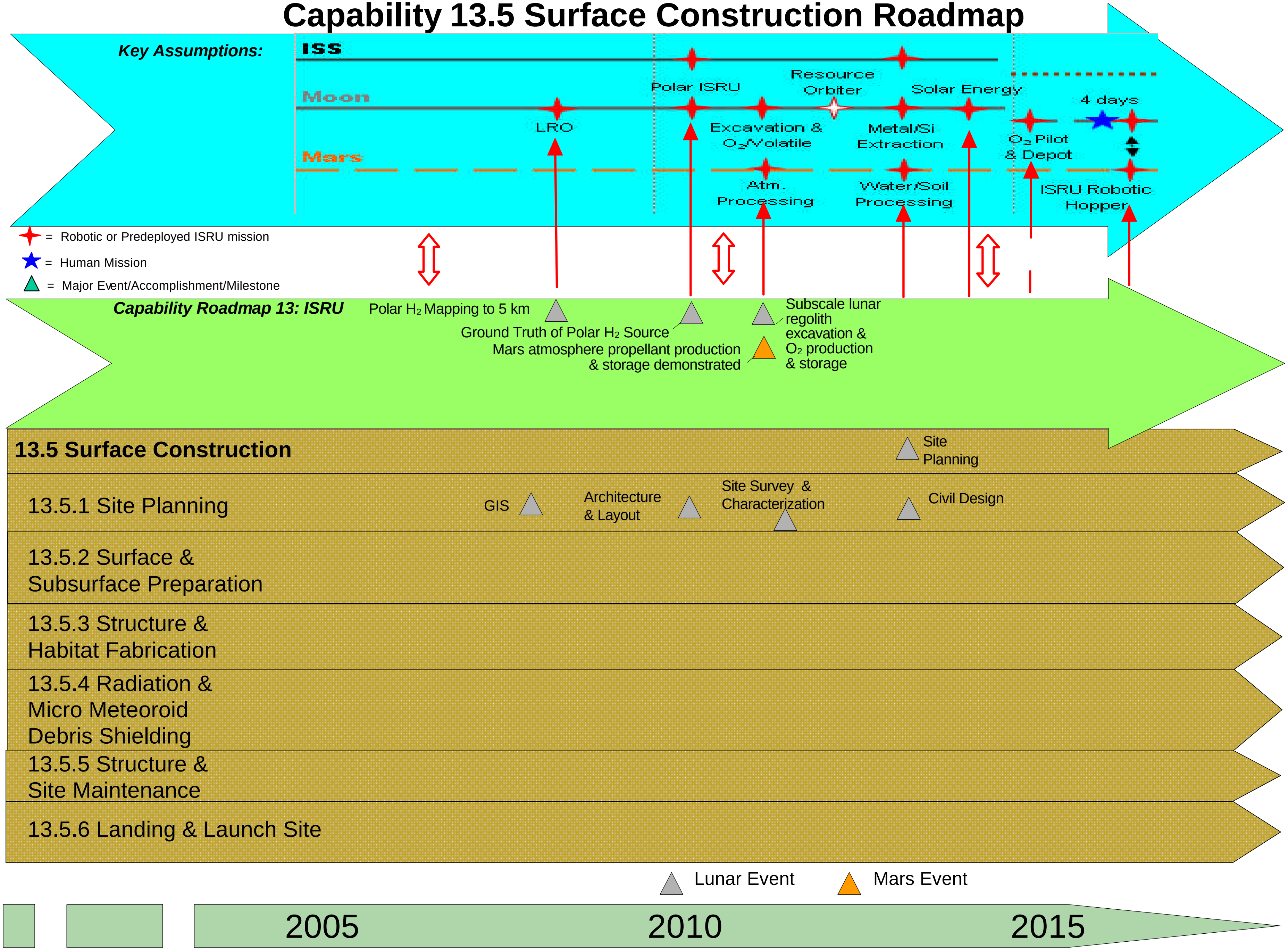
Landing & Launch Site →

Resource Transportation
- Landing & Launch site for off surface resource transportation

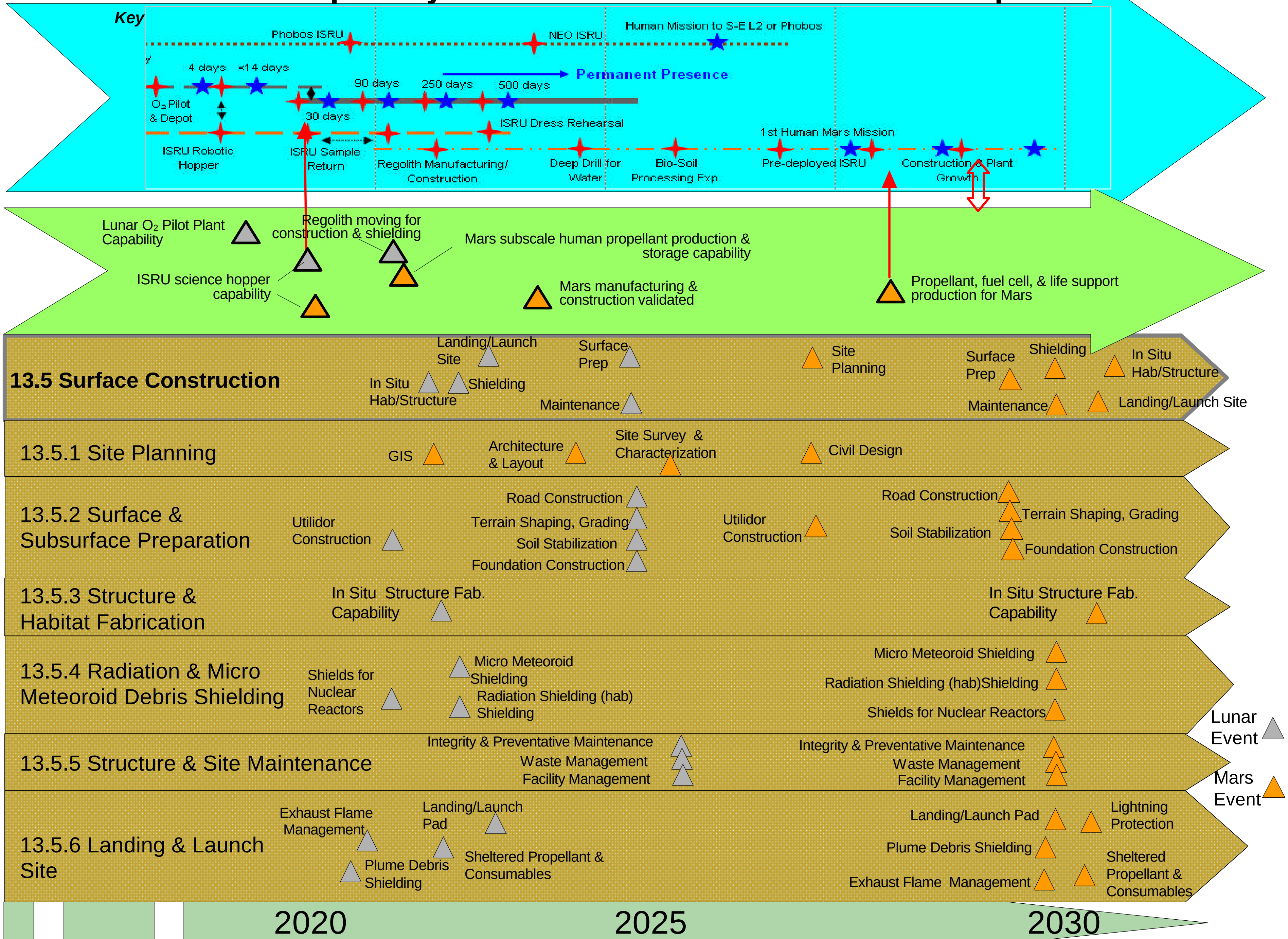
Requirements /Assumptions for Capability 13.5 Surface Construction

- **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



Capability 13.5 Surface Construction Roadmap



Current State-of-the-Art for Capability 13.5 Surface Construction

- **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)
    - Inflatables
    - 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^{-10} 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^{o}C and -20^{o}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 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

Capability	Key Technologies or Sub Capability	Current CRL	Need Date	R&D3
Site Planning	Site Survey & Characterization	1	2014	II
	Architectural Layout & Master Planning	3	2010	I
	Civil Engineering Design	1	2014	I
	Geospatial Information System (GIS) Configuration Control Tool	3	2008	II
Surface & Subsurface Preparation (General)	Road Construction	1	2025	III
	Foundation Construction	1	2025	II
	Utilidor Construction	1	2020	I
	Terrain Shaping, Grading & Rock Clearing	1	2025	II
	Underground Structures	1	2030	III
	Soil Stabilization (Mars Dust)	1	2030	I
Structure & Habitat Fabrication	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	1	2025	II
	In Situ Building Materials	1	2025	I
	Access & Handling Equipment	1	2025	II
	In Situ Robotic / Human Construction Equipment	1	2025	III
Radiation & Micro Meteoroid Debris Shielding	Radiation Shelter (habitat, permanent)	1	2022	II
	Radiation Shields for Nuclear Reactors	1	2020	I
	Micro Meteoroid Shielding (habitat, permanent)	1	2022	I
Structure & Site Maintenance	Integrity & Preventative Maintenance	1	2025	III
	Waste Management	1	2025	III
	Facility Management	1	2025	II
Landing & Launch Site	Landing/Launch Pad	1	2022	III
	Plume Debris Shielding	1	2022	II
	Exhaust Flame Management	1	2021	III
	Sheltered Propellant & Consumable Farms	1	2022	I
	Mars Lightning Protection	1	2030	IV

Maturity Level – Technologies for 13.5 Surface Construction

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Autonomous Site Survey (Orbital /Surface)	Site Survey & Characterization	4	II	2012
Autonomous Geophysical Characterization (Orbital/Surface)	Site Survey & Characterization	4	IV	2012
Architectural Layout CAD Models	Architectural Layout & Master Planning	9	I	2009
Master Planning	Architectural Layout & Master Planning	9	I	2008
Civil Engineering Design CAD Drawings	Civil Engineering Design	5	I	2014
Standards for Planetary Civil Design	Civil Engineering Design	1	II	2008
Construction Methods and Schedules	Civil Engineering Design	2	II	2010
GIS/Configuration Control software	Geospatial Information System (GIS) Configuration Contrl Tool	9	I	2005
Planetary Data Sets	Geospatial Information System (GIS) Configuration Contrl Tool	6	II	2008
Bulldozers & Graders	Road Construction	1	II	2022
Backhoe/Excavators	Road Construction	1	II	2022
Bucket Loaders	Road Construction	1	II	2022
Stabilization techniques & equipment	Road Construction	1	II	2022
Dust Mitigation	Road Construction	1	I	2022
Regolith Crusher & conveyors	Road Construction	1	II	2022
Compactors	Road Construction	1	II	2022
Paving Machine	Road Construction	1	II	2022
Microwave sintering	Road Construction	3	II	2022
LGPS (Lunar GPS)	Road Construction	1	II	2022
Hand Tools	Road Construction	6-9	II	2015
Backhoe/Excavators	Foundation Construction	1	II	2022
Augers/Drilling/Piling	Foundation Construction	1	II	2020
Compaction equipment	Foundation Construction	1	II	2020
Microwave sintering	Foundation Construction	3	III	2022
Protective barriers	Foundation Construction	1	II	2020

Maturity Level – Technologies for 13.5 Surface Construction (2)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Blockout materials for pass through access for utilities	Foundation Construction	1	II	2020
Thermal barrier insulation	Foundation Construction	1	II	2020
Hand Tools	Foundation Construction	6-9	II	2015
Trenchers	Utilidor Construction	2	I	2016
Microwave Sintering	Terrain Shaping, Grading & Rock Clearing	3	III	2022
Bulldozers & Graders	Terrain Shaping, Grading & Rock Clearing	1	II	2022
Backhoe/Excavators	Terrain Shaping, Grading & Rock Clearing	1	II	2022
Horizontal Construction Equipment	Underground Structures	1	III	2026
Vertical Construction Equipment	Underground Structures	1	IV	2026
Precision Navigation/Control Equipment	Underground Structures	2	II	2026
Interlocking brick pavers	Soil Stabilization (Mars Dust)	1	II	2026
flexible mesh netting	Soil Stabilization (Mars Dust)	3	I	2026
Soil Stabilizers	Soil Stabilization (Mars Dust)	1	I	2026
Rigid Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	3	I	2021
Low Pressure Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	I	2021
Transparent Greenhouse Structure	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	III	2021
Rigidized Frames Inflatables	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	I	2021
Traditional Aluminum (ISS alloys)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	9	I	2021
Carbon-based Composites	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	6	II	2021
Nanotube-based Composites	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	IV	2021
Transhab design (Kevlar-based)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	5	II	2021

Maturity Level – Technologies for 13.5 Surface Construction (3)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Mod. Transhab design (Vectran)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	4	II	2021
Inflatable Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	II	2021
Lava Tube or Cave formable inflatables	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	II	2025
In Situ Concrete	In Situ Building Materials	2	I	2021
Vertical Access Device	Access & Handling Equipment	1	II	2021
Scaffolding Functionality Device	Access & Handling Equipment	1	I	2021
Pallets	Access & Handling Equipment	1	I	2021
Cranes	Access & Handling Equipment	1	II	2021
Fork Lifts	Access & Handling Equipment	1	II	2021
Low Maintenance Construction Equipment	Access & Handling Equipment	2	III	2021
Stiff Legged Derricks	Access & Handling Equipment	1	II	2021
Jib Hoist	Access & Handling Equipment	1	II	2021
Robotic Brick Layer	In Situ Robotic / Human Construction Equipment	1	III	2021
In Situ Automated Forming System	In Situ Robotic / Human Construction Equipment	1	IV	2021
Robotic Construction Assistence	In Situ Robotic / Human Construction Equipment	1	III	2021
ISS heritage	Radiation Shelter (habitat, permanent)	9	I	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2018
Lava Tubes	Radiation Shelter (habitat, permanent)	5	II	2018
ISS heritage	Radiation Shelter (habitat, permanent)	9	II	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2016

Maturity Level – Technologies for 13.5 Surface Construction (4)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Lava Tubes	Radiation Shelter (habitat, permanent)	5	II	2018
ISS heritage	Radiation Shelter (habitat, permanent)	9	II	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2016
Bulk Regolith Radiation Shielding	Radiation Shelter (habitat, permanent)	3	I	2018
Bulk Regolith Radiation Shielding	Radiation Shields for Nuclear Reactors	3	I	2016
In-situ Processed Radiation Shielding Material	Radiation Shields for Nuclear Reactors	2	III	2016
Transhab design (Kevlar/Nextel)	Micro Meteoroid Shielding (habitat, permanent)	6	I	2018
Bulk Regolith Radiation Shielding	Micro Meteoroid Shielding (habitat, permanent)	3	I	2018
ISS design (Aluminum/Kevlar/Nextel)	Micro Meteoroid Shielding (habitat, permanent)	9	I	2018
Whipple Shields	Micro Meteoroid Shielding (habitat, permanent)	6	II	2018
Rigid structure (ISS epoxy patch)	Integrity & Preventative Maintenance	6	I	2021
Rigid (microwave-heated nanotube)	Integrity & Preventative Maintenance	1	III	2021
Erection and Environment Sealing	Integrity & Preventative Maintenance	3	II	2021
Systems monitoring / Remote sensing	Integrity & Preventative Maintenance	7	I	2021
Self-repairing systems (pipes)	Integrity & Preventative Maintenance	7	I	2021
Self-repairing systems (insulation)	Integrity & Preventative Maintenance	2	III	2021
automated response systems	Integrity & Preventative Maintenance	7	I	2021
Planetary Surface Containment Systems	Waste Management	2	I	2021
Salvaging	Waste Management	1	III	2021
Re-processing	Waste Management	1	IV	2021
Disposal	Waste Management	1	I	2021
non destructive testing and evaluation	Facility Management	2	I	2021

Maturity Level – Technologies for 13.5 Surface Construction (5)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
wireless structural systems monitoring / Remote sensing	Facility Management	7	I	2021
automatic shutdown / evacuation	Facility Management	5	II	2021
Learning systems	Facility Management	7	II	2021
Special regolith stabilizers/pavers	Landing/Launch Pad	1	II	2017
Pre-cast concrete slabs	Landing/Launch Pad	2	I	2017
Microwave Sintering	Landing/Launch Pad	1	III	2017
Autonomous Debris Clearing	Landing/Launch Pad	2	II	2017
Special regolith stabilizers/pavers	Plume Debris Shielding	3	II	2017
Bulk Regolith Shielding	Plume Debris Shielding	3	I	2017
Wire Mesh Containment	Plume Debris Shielding	3	I	2017
Special regolith stabilizers/pavers	Exhaust Flame Management	3	III	2016
Exhaust Deflectors/Containment	Exhaust Flame Management	3	IV	2016
Bulk Regolith Shielding	Sheltered Propellant & Consumable Farms	3	I	2017
Catenary Wire System	Mars Lightning Protection	1	I	2026
Electrostatic Shield	Mars Lightning Protection	1	V	2026
Mars Grounding System	Mars Lightning Protection	1	I	2026

Metrics for 13.5 Surface Construction

Technology	Current SOA (kg/day, W/kg, etc)	Goal (kg/day, W/kg, etc)
Autonomous Site Survey (Orbital /Surface)	meters	mm
Autonomous Geophysical Characterization (Orbital/Surface)	Orbital Mass Spec	Geo Mapping
Architectural Layout CAD Models	3D CAD Models	3D CAD Models
Civil Engineering Design CAD Drawings	3D CAD Models	3D CAD Models
Standards for Planetary Civil Design	Academic Papers	Design Standards
Construction Methods and Schedules	Concepts	Demos
GIS/Configuration Control software	GIS - COTS	GIS - Custom
Planetary Data Sets	Fractional Coverage	Global
Bulldozers & Graders	0 kg/hr	1000 kg/hr
Backhoe/Excavators	0 kg/hr	500 kg/hr
Bucket Loaders	0 kg/hr	500 kg/hr
Stabilization techniques & equipment	0 m^2	250 km^2
Dust Mitigation	0 m^2	250 km^2
Regolith Crusher & conveyors	0 kg/hr	TBD kg/hr
Compactors	0 m^2	250 km^2
Paving Machine	0 m^2	250 km^2
Microwave sintering	<5 cm	>15 cm
LGPS (Lunar GPS)	0 cm^2	10 cm^2
Hand Tools	Apollo	Effective
Backhoe/Excavators	0 kg/hr	500 kg/hr
Augers/Drilling/Piling	0 kg/hr	TBD
Compaction equipment	0 m^2	250 km^2
Microwave sintering	<5 cm	>15 cm
Protective barriers	0 m^2	250 km^2
Blockout materials for pass through access for utilities	>1m^2	>1m2
Thermal barrier insulation	0 w/m^2	TBD w/m^2
Trenchers	0 m deep	<.5 m deep
In Situ Concrete	0	100 m^3

Metrics for 13.5 Surface Construction (2)

Technology	Current SOA (kg/day, W/kg, etc)	Goal (kg/day, W/kg, etc)
Vertical Access Device	0	10 m vertical access
Scaffolding Functionality Device	0	10 m vertical access
Pallots	0	1000 kg
Fork Lifts	0	5,000 kg
Stiff Legged Derricks	0	5,000 kg
Jib Hoist	0	1,000 kg
Robotic Brick Layer	0	250 bricks/day
In Situ Automated Forming System	0	100 m^3
Robotic Construction Assistence	0	100 kg
Radiation Transport Modeling	25 rem/mo (EVA STD)	Earth-like conditions (~.36 rem/yr)
Lava Tubes	TBS	Earth-like conditions (~.36 rem/yr)
Polyethylene/nanotube structure	0	Earth-like conditions (~.36 rem/yr)
Bulk Regolith Radiation Shielding	25 rem/mo	Earth-like conditions (~.36 rem/yr)
In-situ Processed Radiation Shielding Material	TBS	No radiation contamination of Lunar environment
Bulk Regolith Radiation Shielding	As required by design	No habitat or personnel penetrations
Whipple Shields	As required by design	No habitat or personnel penetrations
Self-repairing systems (pipes)	0	repair within 80-90% of initial design characteristics
Self-repairing systems (insulation)	0	repair within 80-90% of initial design characteristics
Planetary Surface Containment Systems	0	100 M^3
Salvaging	0	80% of waste
Re-processing	0	60% of unsalvagable waste
Disposal	0	20% oi unsalvageble waste
automatic shutdown / evacuation	no automatic shutdown	automatic shutdown
Learning systems	0	self updating systems
Autonomous Debris Clearing	Ejecta	No Ejecta
Exhaust Deflectors/Containment	Uncontrolled Flame	Controlled Flame
Catenary Wire System	No Protection	Full Protection
Electrostatic Shield	No Protection	Full Protection

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

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- 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**

Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

- 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)

Surface ISRU Product and Consumable Storage and Distribution

- In-Situ Resource Utilization 13.0
  - Resource Extraction 13.1
  - Material Handling & Transport 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
    - Surface Cryogenic Fluid & Propellant Storage & Distribution 13.6.1
      - Passive Liquefaction and Cooling 13.6.1.1
      - Active Liquefaction 13.6.1.2
      - Cryogenic Storage & Insulation Systems 13.6.1.3
      - Cryogenic Distribution and Recovery 13.6.1.4
    - Chemical Reagent Storage & Distribution 13.6.2
      - Reagent Storage 13.6.2.1
      - Reagent Distribution 13.6.2.2
    - Gas Storage & Distribution 13.6.3
      - Low Pressure Storage 13.6.3.1
      - High Pressure Storage 13.6.3.2
      - Distribution & Recovery 13.6.3.3
    - Water & Earth Storable Fluid Storage & Distribution 13.6.4
      - Deployable Storage 13.6.4.1
      - Rigid Storage 13.6.4.2
      - Detached Storage 13.6.4.3
      - Distribution 13.6.4.4
    - Utility Connections & Interfaces 13.6.5
      - Thermal Management 13.6.5.1
      - Umbilicals and Interfaces 13.6.5.2
    - Hazard Detection & Suppression 13.6.6
      - Leak Detection 13.6.6.1
      - Self-Healing Systems 13.6.6.2
      - Hazard Suppression Systems/Techniques 13.6.6.3
  - ISRU Unique Development & Certification Capabilities 13.7

Requirements /Assumptions for 13.6 ISRU Product Storage & Distribution

- 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

Team 13: In-Situ Resource Utilization

Products From Storage & Distribution	Capability	Capability Products To Storage and Distribution
• Fuel Cell Reactant Storage & Distribution • Propellant Storage & Distribution	High-Energy Power & Propulsion (2)	• Solar & nuclear power to support power-intensive ISRU activities
• Fluid storage and distribution for transfer to in-space depots	In-Space Transportation (3)	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Storage & Distribution of fuel cell reagents for rovers • Propellant storage & distribution for surface hoppers or large sample return missions	Robotic Access to Planetary Surfaces (6)	• Interface coordination for fluid transfer • Water by-products of rover fuel cells
• Propellant storage & distribution for lander reuse	Human Planetary Landing Systems (7)	• Interface Coordination for fluid transfer • Delivery of ISRU capabilities to sites of exploration
• Gases for habitat inflation & buffer gases • Life support consumable storage & distribution	Human Health and Support Systems (8)	
• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 & water distribution for EVA	Human Exploration Systems & Mobility (9)	• Interface coordination for fluid transfer • Water by-products of rover fuel cells
• Fluid storage & distribution	Autonomous Systems & Robotics (10)	• Robots/rovers to perform maintenance & repair • Software & Failure Detection and Repair logic for autonomous operation
	Scientific Instruments & Sensors (12)	• Highly reliable, self calibrating instrumentation and sensors

Storage and Distribution Interdependency with other ISRU Elements

Team 13: In-Situ Resource Utilization

ISRU Element Products To → **Storage & Distribution** → **Products To ISRU Elements**

ISRU Element Products To

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

Storage & Distribution

- Cryogenic Fluids
- Chemical Reagents
- Gases
- Water/Earth Storable Fluids
- Utility Connection & Interfaces
- Hazard Detection & Suppression

Products To ISRU Elements

Resource Extraction
- Fluids for extraction processes

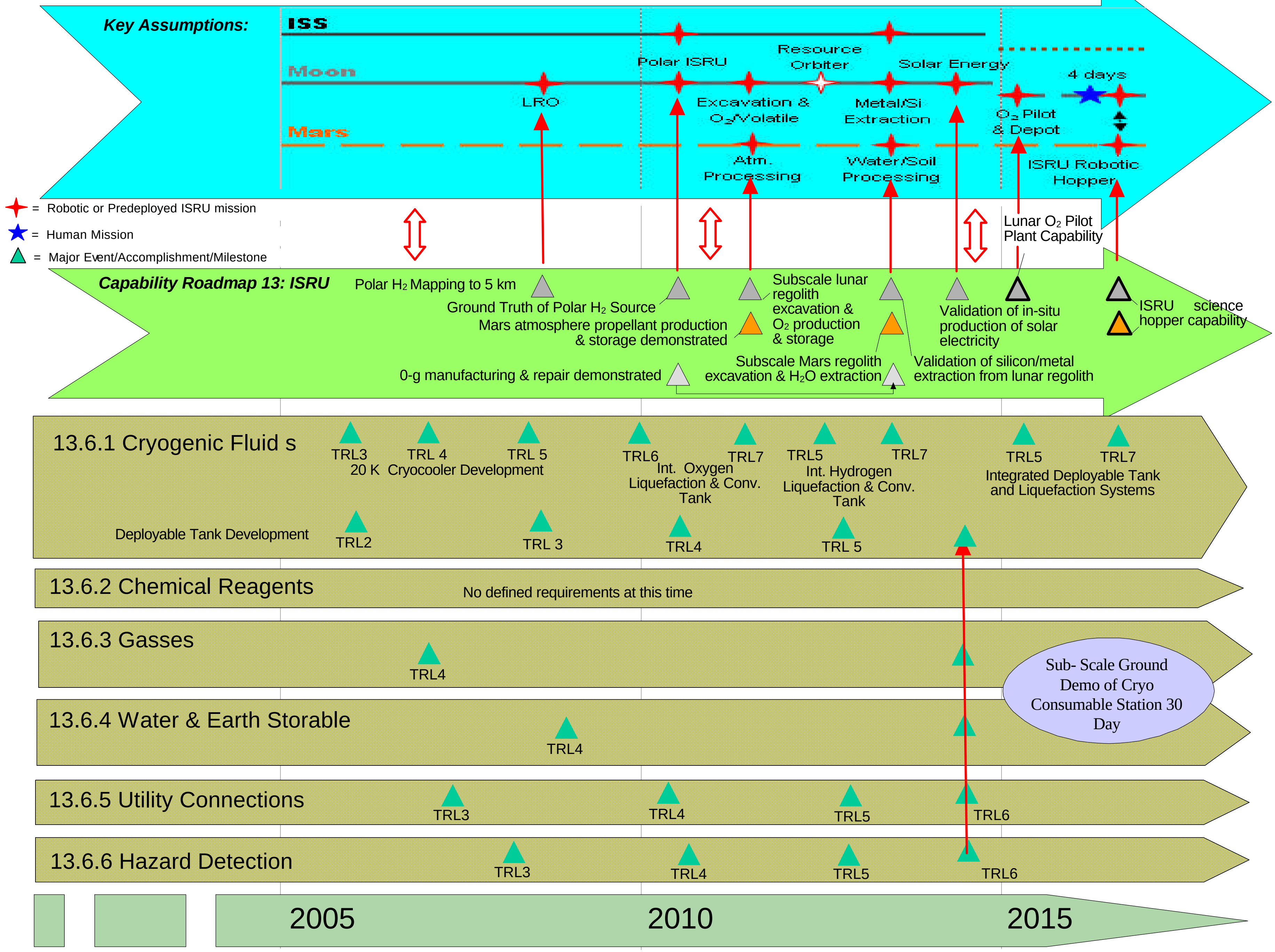
Resource Transportation
- Fluids for transportation vehicles

Resource Processing
- Process fluid replenishment
- Water for reprocessing

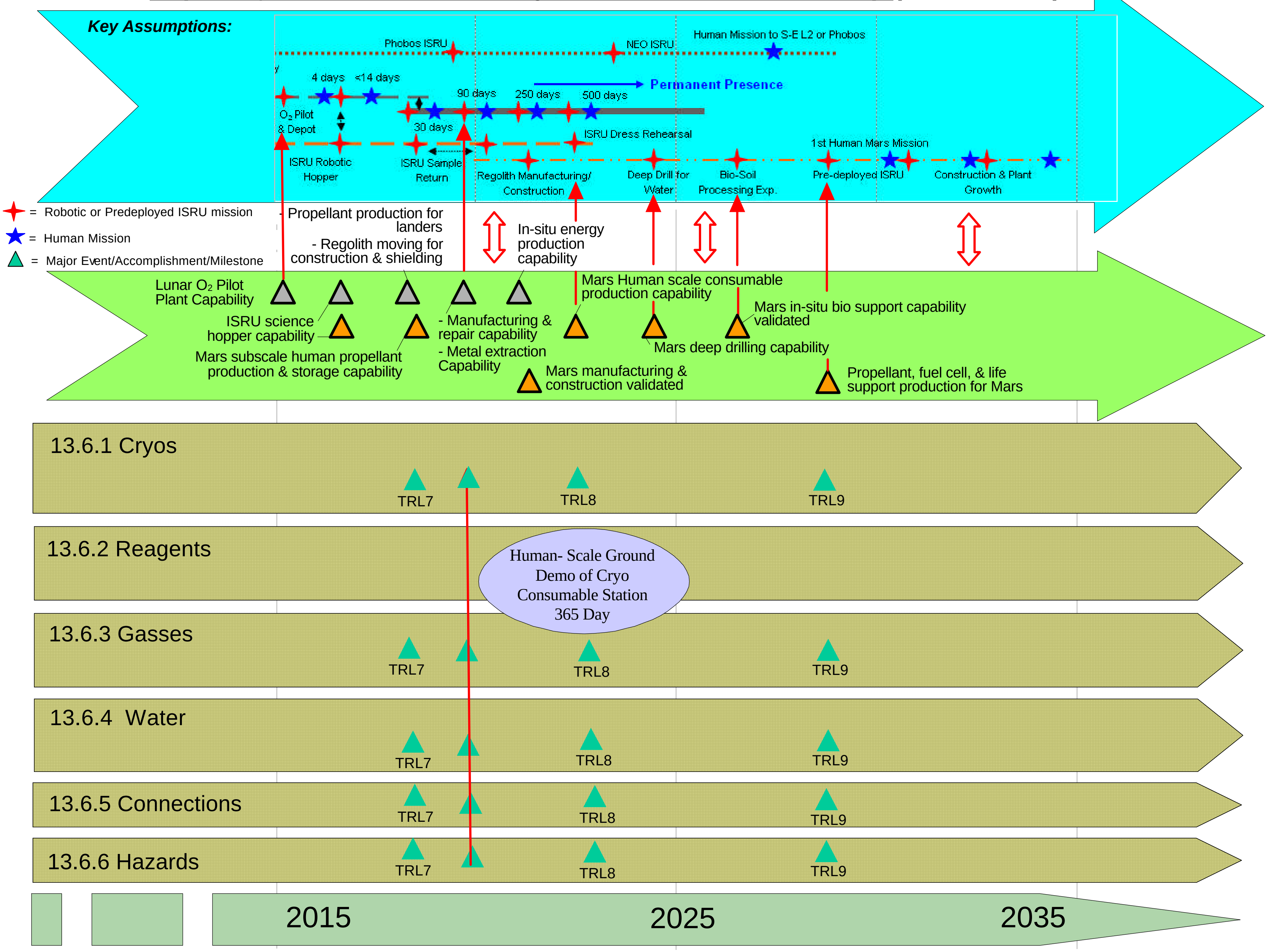
Surface Manufacturing
- Fluids for manufacturing processes

Surface Construction
- Fluids for construction vehicles & equipment

Capability Team 13: ISRU Storage and Distribution Roadmap (2005 to 2015)



Capability Team 13: ISRU Storage and Distribution Roadmap (2015 to 2035)



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

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
Cryogenic Fluid Storage and Distribution	*20K Cryocoolers, 100's of Watts cooling*	1	*III*	2012
	80K Cryocoolers, 100's of watts cooling	1	*II*	2010
	Low Launch Volume Cryogenic Storage Tank	1	*III*	2012
	Insulation systems	3	*II*	2012
	Long life compressors & motors	2	*II*	2016
	Deployable Transfer Lines	2	*III*	2016
	Portable Tanker Development	3	*II*	2014
	Low mass/volume components	2	*II*	2014
Gas Storage and Distribution	Low Pressure deployable	2	*II*	2014
	Sorption systems	1	*II*	2016
	Multi-phase systems	2	*II*	2016
	High Pressure deployable	2	*II*	2020
	Long life compressors & motors	2	*II*	2016
	Deployable high pressure lines	2	*II*	2020
	Portable Gas cylinder development	3	*II*	2014
	Low mass/volume components	2	*II*	2014
	Recovery Systems	2	*II*	2016

Maturity Level – Capabilities for Storage and Distribution

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
Water and Earth Storable Storage & Dist.				
	Deployable Storage	1	*I*	2016
	Detachable Storage	1	*II*	2020
	Distribution System Development	2	*I*	2016
Utility Connections and Interfaces	Adv Thermal Management Systems	2	*II*	2016
	Adv Thermal Management Devices	2	*II*	2012
	Automated Umbilicals	2	*I*	2014
	Self-healing Seals	1	*II*	2014
	Low mass/volume Components	1	*II*	2014
	Long life Drive Motors	1	*II*	2016
Hazard Detection and Suppression	Point Sensor Development	2	*II*	2014
	Gas Chromatograph/Mass Spectrometer	1-2	*III*	2014
	Nano Sensors	2	*III*	2014
	Self-healing Systems	2	*III*	2014
	Hazard suppression systems	3	*III*	2014
	Halon Replacement	2	*II*	2014

Maturity Level – Technologies Storage and Distribution

Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
20K Cryocoolers, 100’s of Watts	*CFSD*	*2*	*III*	2014
80K Cryocoolers, 100’s of watts cooling cooling	*CFSD*	*4*	*II*	2014
Low Launch Volume Cryo Storage Tank	*CFSD*	*2*	*III*	2014
Insulation systems	*CFSD*	*5*	*II*	2010
Long life compressors & motors	*CFSD, GSD*	*4*	*II*	2010
Deployable Transfer Lines	*CFSD*	*2*	*III*	2014
Portable Tanker Development	*CFSD*	*3*	*II*	2014
Low mass/volume components	*CFSD, GSD, UCI*	*3-6*	*II*	2014
Low Pressure deployable	*GSD*	*3*	*II*	2010
Sorption systems	*GSD*	*4*	*II*	2010
Multi-phase systems	*GSD*	*4*	*II*	2014
High Pressure deployable	*GSD*	*2*	*II*	2014
Deployable high pressure lines	*GSD*	*2*	*II*	2016
Portable Gas cylinder development	*GSD*	*5*	*II*	2014
Recovery Systems	*GSD*	*3*	*II*	2014

Maturity Level – Technologies Storage and Distribution

Team 13: In-Situ Resource Utilization

Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
Deployable Storage	*WSD*	*4*	*I*	2014
Detachable Storage	*WSD*	*4*	*II*	2014
Distribution System Development	*WSD*	*4*	*I*	2014
Adv Thermal Management Systems	*UCI*	*2*	*II*	2020
Adv Thermal Management Devices	*UCI*	*2*	*II*	2020
Automated Umbilicals	*UCI*	*3*	*I*	2014
Self-healing Seals	*UCI*	*2*	*II*	2014
Long life Drive Motors	*UCI*	*4*	*II*	2014
Point Sensor Development	*HDS*	*3*	*II*	2014
Gas Chromatograph/Mass Spectrometer	*HDS*	*4*	*III*	2014
Nano Sensors	*HDS*	*2*	*III*	2020
Self-healing Systems	*HDS*	*2*	*III*	2020
Hazard suppression systems	*HDS*	*2*	*III*	2020
Halon Replacement	*HDS*	*4*	*II*	2014

Metrics for Storage & Distribution

- 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)

Metrics for Storage & Distribution

- 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

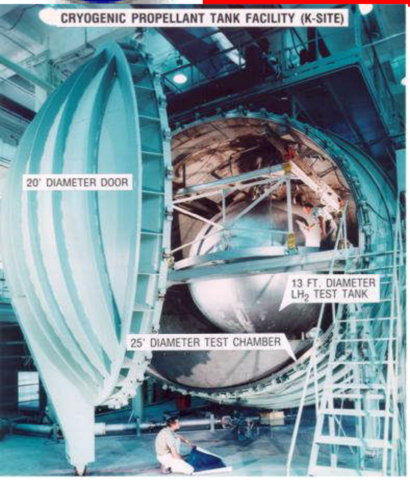
- Several SBIR/STTR Phase II projects in recent years
  - Insulation systems
  - Cryocoolers
  - Valve technology
  - Automated umbilical
  - Gas detection sensors

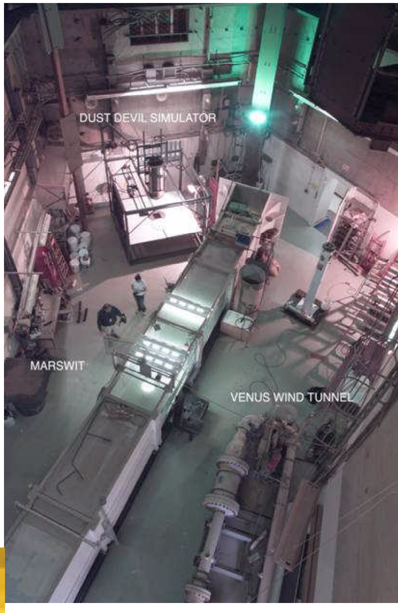
Technology Gaps for Storage & Distribution

- 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

Capability Development Strategy
(Same as Resource Processing)

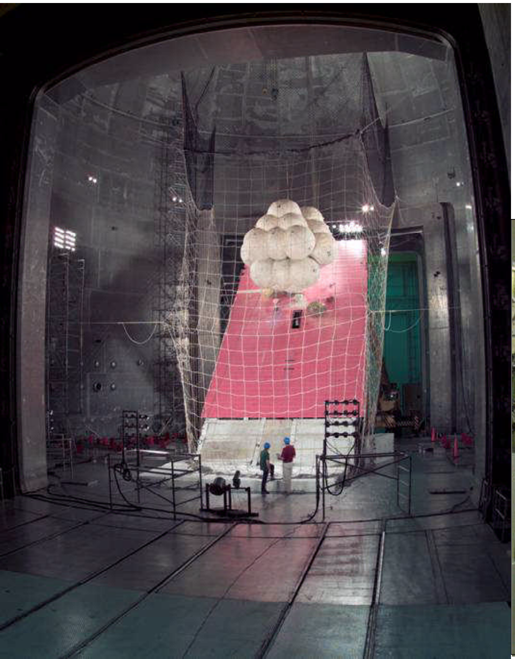
- There Is No One "Best Solution" For Storage and Distribution of fluids on the moon and Mars.
  - One Technology May Trade Better Than Another Depending On The Architecture
- As Architecture Options Mature Trade Studies Will Be Used To Down Select To A Set Of Technologies That Have The Potential Meet 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.

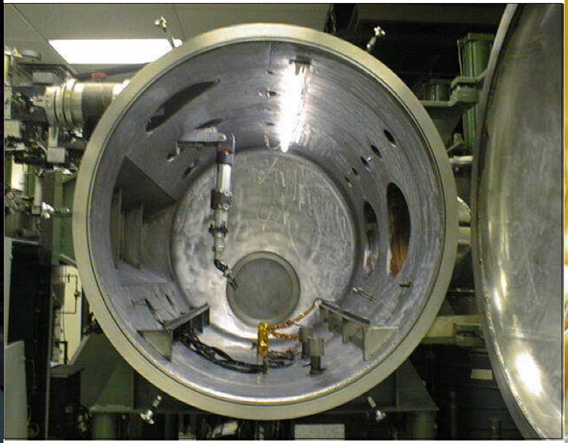




ISRU Capability Element 13.7
ISRU Unique Test and Certification

Diane Linne and Michael Downey
NASA Co-Leads





Unique Test and Certification Roadmap Element Team

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

Team 13: In-Situ Resource Utilization

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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_2O_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	Capability	Products to Unique Test/Cert
Unique Lunar and Mars test environment plus: • Simulants for solar array development	High-energy power and propulsion (2)	• Compact power for surface demos
• Long-term dust effects on ascent propulsion system operations • Soil mechanics models for rocket plume cratering analysis	In-space transportation (3)	
• Dust accumulation/removal on optics for surface telescopes	Advanced telescopes and observatories (4)	
• Soil mechanics for tire/soil interaction	Robotic access to planetary surfaces (6)	• in-situ measurement of soil properties • possible sample returns
• Long-term dust effects on spacesuits, life support systems, etc.	Human Health and Support Systems (8)	
• Long-term dust effects on mobility systems • Simulation/modeling of surface regolith/compactness for rovers	Human Exploration Systems & Mobility (9) Autonomous Systems & Robotics (10)	
• Opportunity to piggy-back on tests in unique environments	Scientific Instruments & Sensors (12)	• Advanced sensors and instruments for tests • Advanced sensors and instruments for robotic in-situ measurements
	Advanced modeling, simulation, analysis (14)	• 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

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

Unique Test and Certification

- Modeling and Standards
- Simulants
- Unique Test Environments - Normal Gravity
- Reduced Gravity Test Environments

Products or Services From Unique Test and Certification

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

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

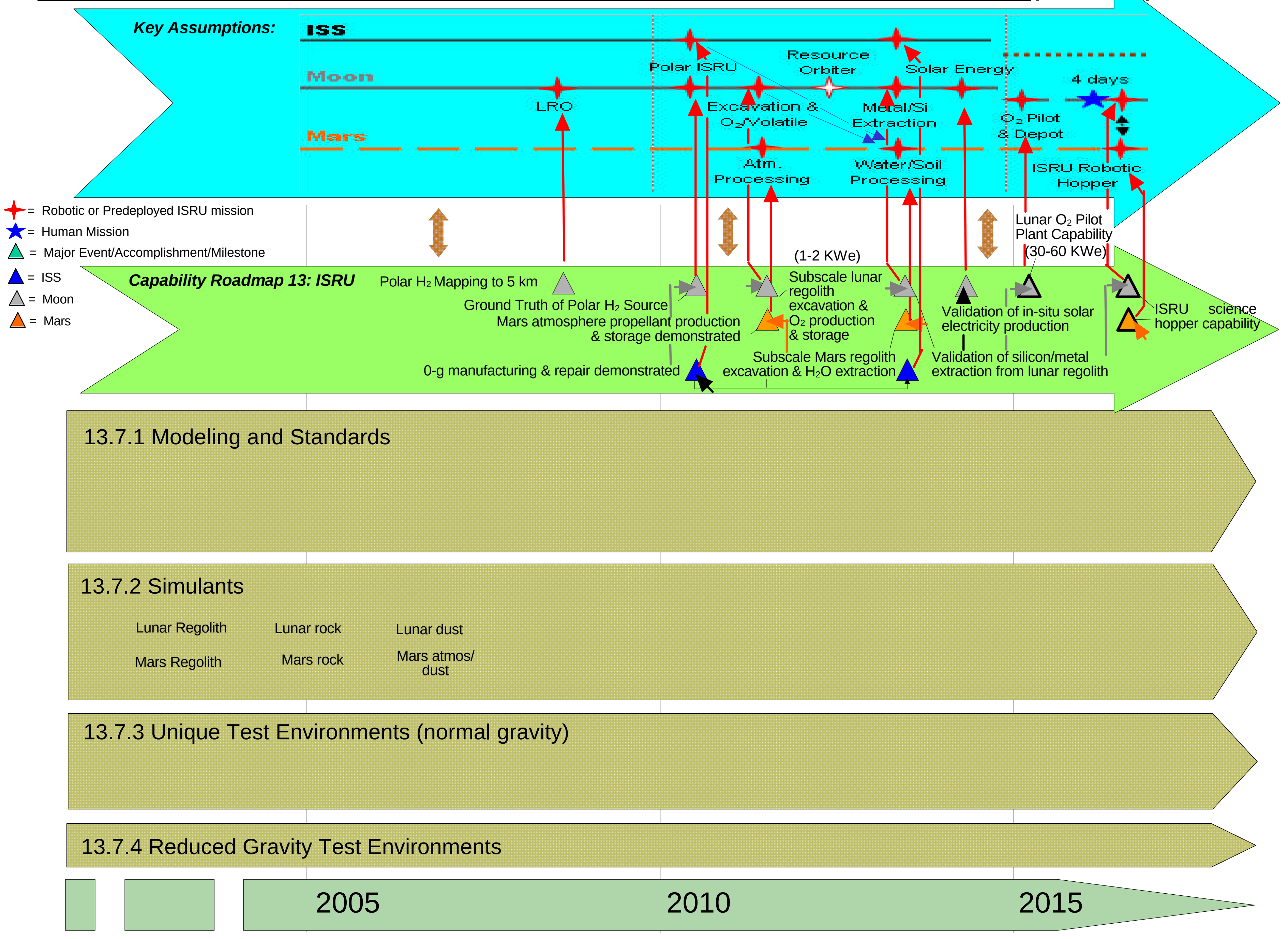
Resource Processing
- All simulant types
- Test and certification environment

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

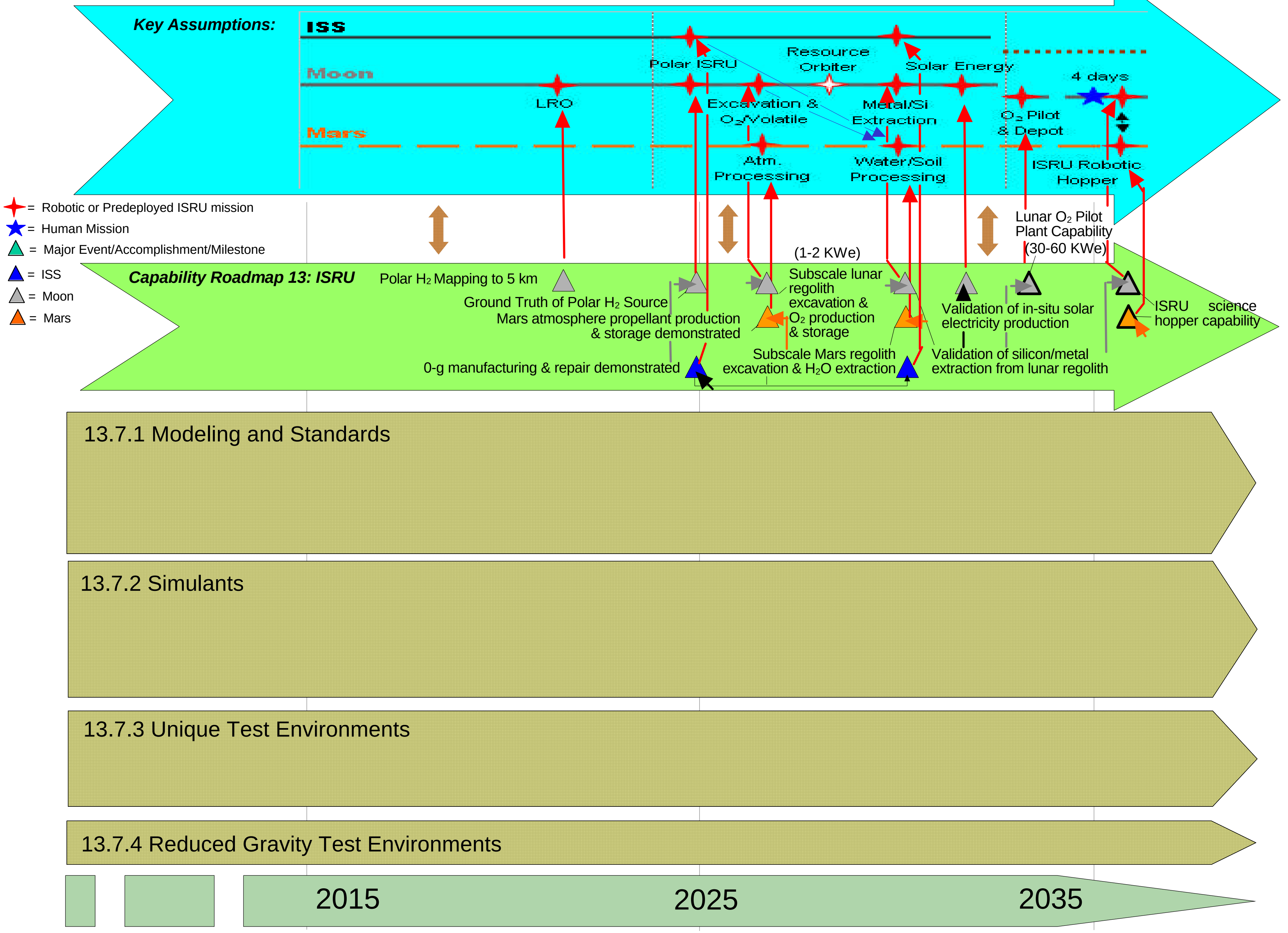
Surface Manufacturing w/ In-Situ
- Dust simulants
- Test and certification environment

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

Capability Team 13: In Situ Resource Utilization (ISRU) Unique Test and Certification Roadmap (2005 to 15)



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



Current State-of-the-Art for Unique Test and Certification

- 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 (5×10^{-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_2O
  - 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

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assesment		
		CRL	R&D3	Need Date
Modeling and Standards	Regolith characterization and behavior - soil mechanics	1	*III*	
	Regolith characterization and behavior - granular flows	1	*III*	
	ISRU component models	2	*II*	
	ISRU system models	1	*II - III*	
	Unique environment design/test standards	1	*II*	
Simulants	Lunar regolith	3	*II*	
	Lunar rock	1	*II*	
	Lunar dust	1	*II*	
	Martian regolith	1	*III*	
	Martian rock	1	*II*	
	Martian dust	1	*III*	
	Martian atmosphere	4	*II*	
	Other Bodies	1	*III*	

Maturity Level – Facility Capabilities

Table is based on preliminary survey of facilities at NASA GRC, KSC, JSC, and ARC, and Lockheed-Martin - many more out there to evaluate (including more industry and DoD)

Test Condition	Requirement	Best Match Found So Far	Key Gaps (R&D3) to get to required condition
Lunar Day	10^{-10} Torr/255 - 390 K	$5x10^{-8}$ torr/ meets temp. requirement	Add helium pumping panels to get down to 10^{-10} torr (III)
Lunar Night	10^{-11} Torr/120 K	$5x10^{-8}$ torr / meets temp. requirement	Add helium pumping panels to get down to 10^{-11} torr (III)
Lunar Poles	10^{-11} Torr/40 K	$5x10^{-8}$ torr / meets temp. requirement	Add helium pumping panels to get down to 10^{-11} torr (III)
Mars (varies by day/night and winter/summer)	300 - 1000 Pa (0.044 - 0.145 psi)/145 - 240 K	several facilities meet pressure and temperature	
Mars Winds	300 km/hr (190 mph)	Meets wind, pressure, and simulants but not temp.	
Ability to accept simulants	dust (<20 microns) regolith (>20 microns)	demonstrated in 10-6 torr facility; possible in 10-7 torr facilities	Requires cryopumps (instead of oil diffusion pumps)
Reduced Gravity (specify g-level and max. time per test)	micro-g 1/6th Earth-g (moon) 0.38 Earth-g (Mars)	yes - long duration 30 seconds max 40 seconds max	Free-flying centrifuge facility for long duration (IV)

Maturity Level – Technologies
Unique Test and Certification

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Quasi-static soils - predictive equations across wide conditions	Reg. characterization & behavior	2	II	
Quasi-static soils - relevant property identification	Reg. characterization & behavior	2	II	
Granular flows - equations of motion	Reg. characterization & behavior	1	III	
Granular flows - constituitive relations	Reg. characterization & behavior	1	III	
Granular flows - relevant property identificatio	Reg. characterization & behavior	2	II	
Ice composition and mechanics included in so models	Reg. characterization & behavior	1	III	
Root Simulant: Basalt-rich material representing Mare (lowlands) locations	Lunar regolith simulants	4	I	
Root simulant: Anorthite and feldspathic basal material representing Terrae (highlands) locations	Lunar regolith simulants	2	I	
Root simulant: Pyroclastic glass	Lunar regolith simulants	2	III	
Derivative simulant: Simulant materials specif to Lunar poles (ice and elemental concentrations)	Lunar regolith simulants	1	V	
Derivative simulant: Dust material (<20micron)	Lunar dust simulants	1	IV	
Derivative simulant: Impact-glass components added (agglutinates, microspheres)	Lunar regolith simulants	2	IV	
Derivative simulant: Nanophase metallic iron inclusions	Lunar regolith simulants	2	IV	
Derivative simulant; Specific mineral additions (e.g., olivine, ilmenite)	Lunar regolith simulants	3	I	
Derivative simulant: Volatile elements incorporation	Lunar regolith simulants	1	IV	
Derivative simulant: Specific chemical composition adjustments	Lunar regolith simulants	4	II	
Lunar rock properties simulations	Lunar rock simulants	1	IV	
Lunar rock simulants production, storage, & distribution	Lunar rock simulants	1	III	
Martian regolith physical properties simulation	Martian regolith simulants	2	III	
Martian regolith chemical properties simulatio	Martian regolith simulants	3	III	

Maturity Level – Technologies
Unique Test and Certification

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Martian regolith mineralogical properties simulation	Martian regolith simulants	2	III	
Martian regolith simulants production, storage & distribution	Martian regolith simulants	3	III	
Martian rock physical properties simulations	Martian regolith simulants	1	V	
Martian rock chemical properties simulations	Martian regolith simulants	1	V	
Martina rock mineralogical properties simulations	Martian regolith simulants	1	V	
Martian rock simulants production, storage, & distribution	Martian regolith simulants	1		
Martian dust physical properties simulation	Martian dust simulants	4	III	
Martian dust chemical properties smulation	Martian dust simulants	2	IV	
Martian dust mineralogical properties	Martian dust simulants	2	V	
Martian dust simulants production, storage, & distribution	Martian dust simulants	1	II	
Martian atmosphere physical properties simulation	Martian simulants	4	I	
Martian atmosphere chemical properties simulation	Martian simulants	4	I	
Planetary moons properties simulations	Other bodies simulants	<1	V	
Asteroids properties simulations	Other bodies simulants	<1	V	
Comets properties simulations	Other bodies simulants	<1	V	

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
- Integrated Environments - thermal, vacuum, dust, *and* gravity

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

Metrics for Unique Test and Certification

- 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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Fundamental Purpose For Commercializing ISRU

- NASA Guiding National Objective 4 (from NASA Strategic Plan, 2005)
  - 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'

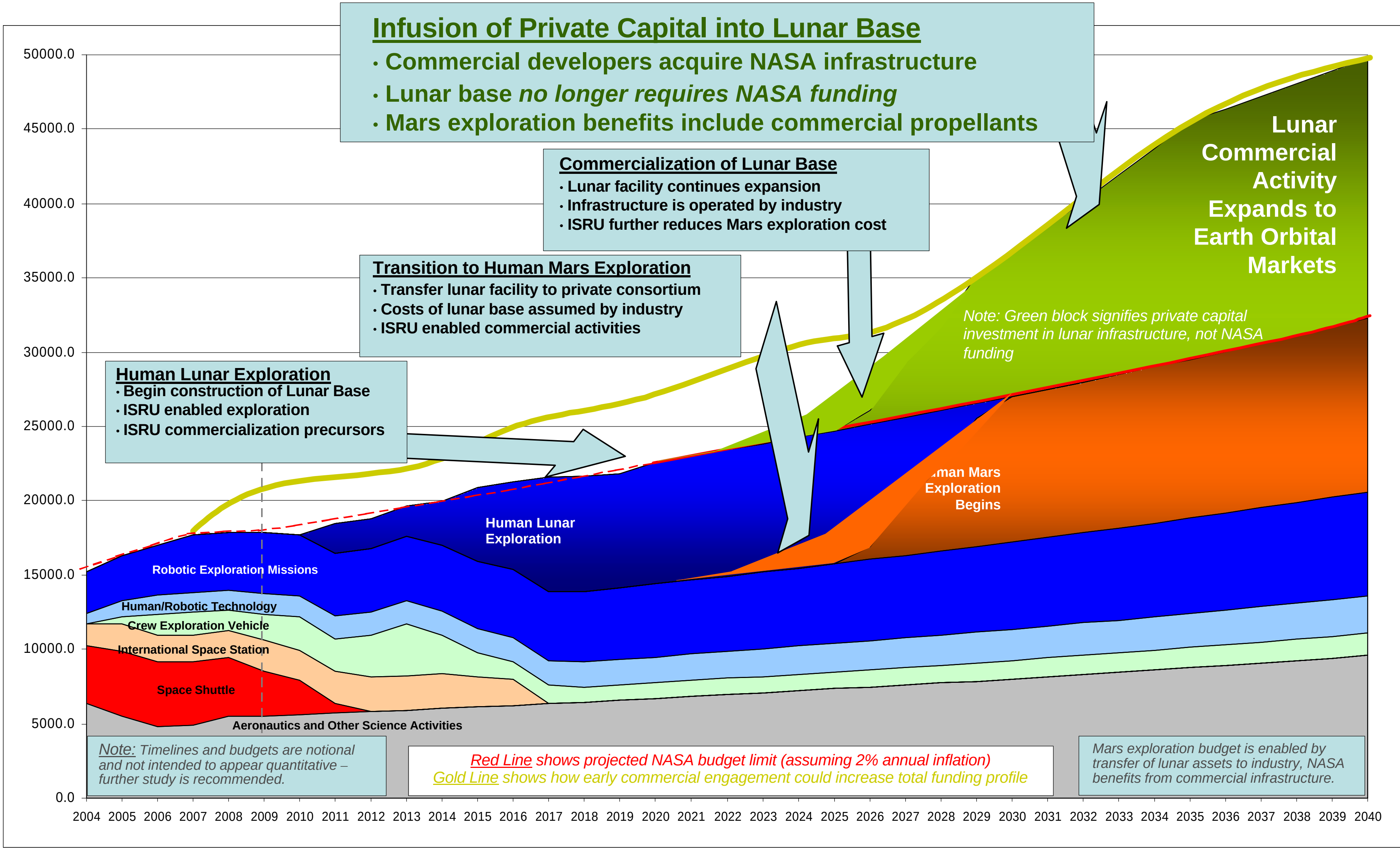
- Money saved due to commercial ISRU and resulting infrastructure can support other aspects of the Space Exploration Program
  - Lunar ISRU commercialization can become a hand-off strategy, enabling human Mars exploration

- 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

Team 13: In-Situ Resource Utilization



Approach to Commercializing ISRU

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

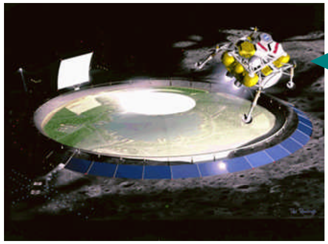
*Selection of Technology is based on optimum cost not performance

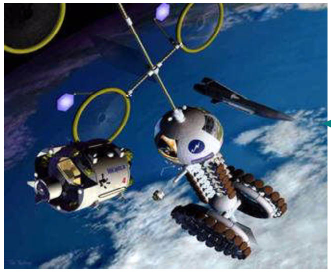
Market Identification

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

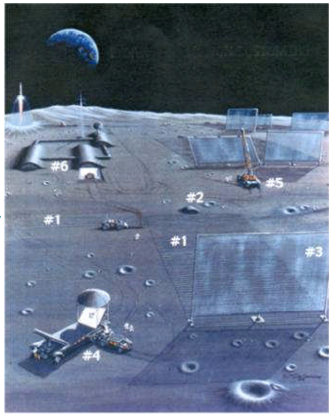
- Possible Market Areas for commercialized space ISRU in next 10 to 15 years
  - Science (NASA): lunar-based astronomical observatories
  - National Security (DOD, DOE):
    - Earth and space surveillance
    - Satellite refueling, space control, debris management
    - Eliminate dependence on foreign 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

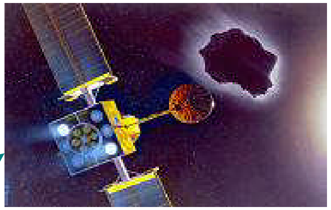
Near & Far Term Space Commercial Applications

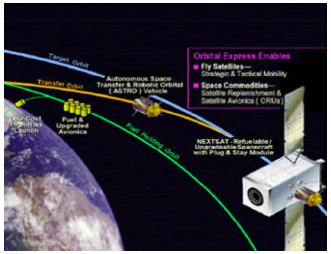




- **Remote Sensing**
  - Earth viewing
  - Astronomical observatories
- **Self-Sustaining Colonies**
  - Tourism
  - Resort construction & servicing
- **Power Generation**
  - Power beaming from lunar surface
  - Helium-3
- **Cis-Lunar Transportation & Propellant**
  At Earth-Moon L1 for following:
  - 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

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

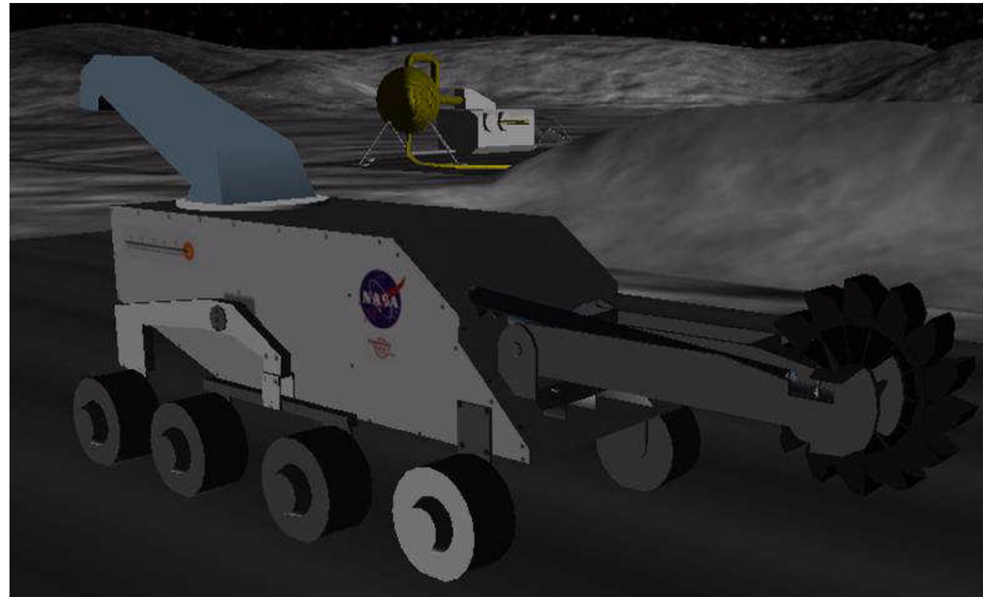
- Begin with projected Human Exploration requirements
  – Initial market: Propellant for Direct-return from Moon to Earth
  – Evaluate other markets and growth in production rate and infrastructure to enable propellant depot at Earth-Moon (EM) L1 for increased human exploration & other markets (i.e. 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

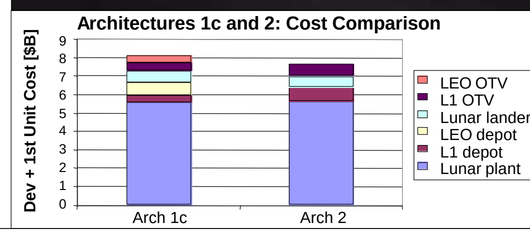
- Case Study: FY02 CSM/NExT Report on *Commercial Feasibility Assessment of Lunar Propellant Production*

Commercial Lunar Propellant Feasibility Study

Project Description

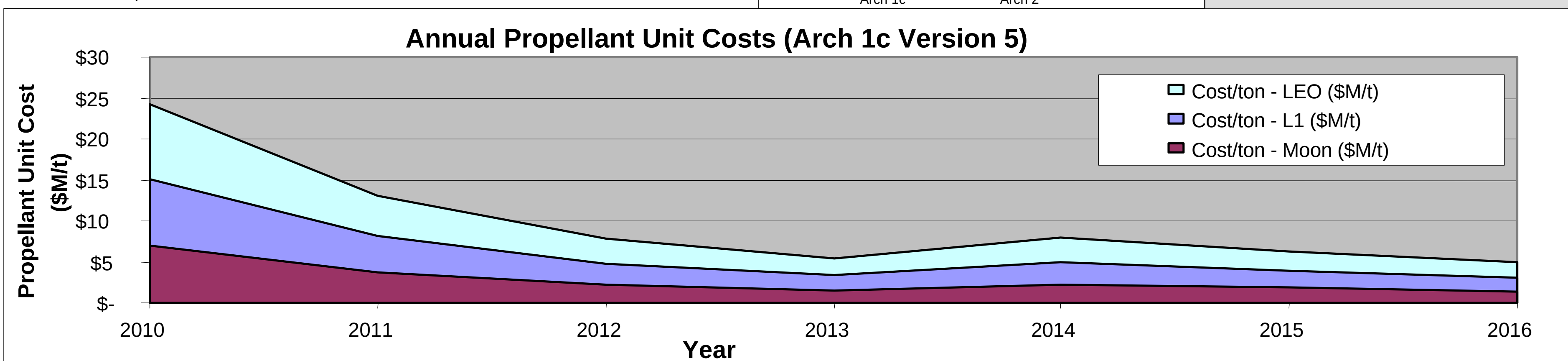
- FY02 Study Funding provided by the NASA Exploration Team (NExT)
- Scope: Examine the ***commercial feasibility*** of lunar-based transportation fuel production and delivery
- Participants: JPL / CSM / CSP Associates, Inc.
- Assumptions
  - Water is produced on the Moon, along with the propellant needed 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



"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

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

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

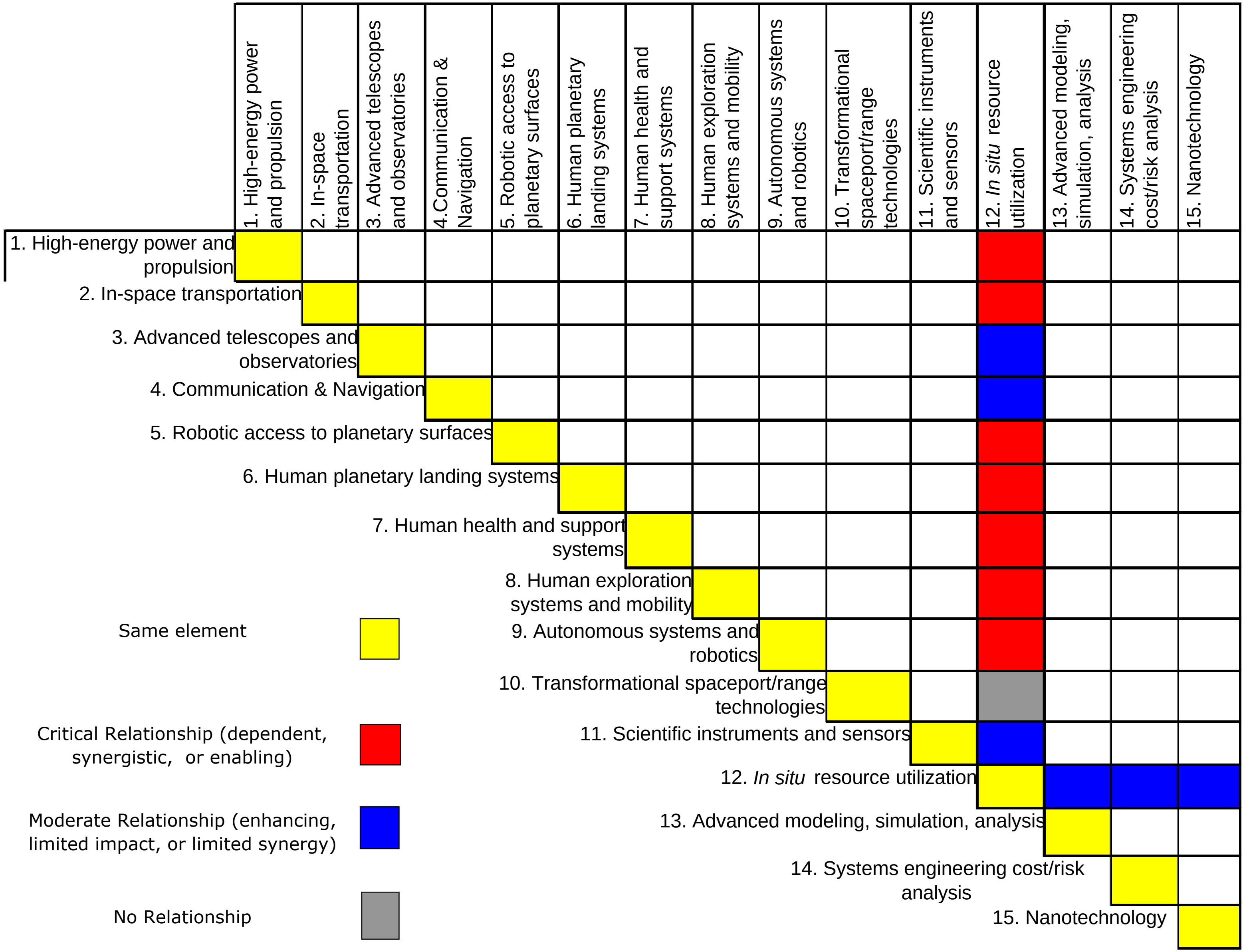
- **Operation in severe environments**
  - Operation and interaction with dust (fine particles are invasive and highly abrasive)
  - Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Methods to mitigate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

Team 13: In-Situ Resource Utilization



Examples of CRM Relationships

Team 13: In-Situ Resource Utilization

	2. In-space transportation	**Capability Flow & Criticality**	**12. In situ resource utilization**	Nature of Relationship
	Ascent /Descent Stages	←	Resource Processing, storage and Distribution	Propellant made on Moon/ Mars may provide significant mass savings
	Earth Departure Stage	←	Resource Processing, storage and Distribution	Propellant made on Moon may be used for Earth (L1) Departure Stage
	Earth Return Stage	←	Resource Processing, storage and Distribution	Propellant made on Mars may be used for Earth Return Stage

	8. Human exploration systems and mobility		**12. In situ resource utilization**	
	Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	Sub-Topic or Subsidiary Capability	Nature of Relationship
	Crew Mobility - Surface Mobility Systems	→	Resource Assessment / Extraction	Geologists will require mobility to access resource areas for evaluation
	Refueling and fluids support systems	←	Surface Consumable & Product Storage and Distribution	Automated umbilicals will supply breathing air, propellants and purges
	Fuel Cell	←	Surface Consumable & Product Storage and Distribution	In Situ Produced Propellants can supply fuel cells for surface mobility

ISRU Interaction w/ Strategic Roadmap Activities

SR-#	Short	Full Name	Chartered Objective	In Situ Resource Utilization (ISRU)	Relationship
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
2	Mars	Robotic and Human Exploration of Mars	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		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
3	Solar System	Solar System Exploration	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.		Search for Solar System Resources
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.		Not Applicable
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.		ISRU can reduce mass launched from Earth
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.		Not Applicable
9	Earth	Earth Science and Applications from Space	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.		Not Applicable
10	Sun-Solar System	Sun-Solar System Connection	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.		Not Applicable
11	Aero	Aeronautical Technologies	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.		ISRU can provide propellants for planetary fliers
12	Education	Education	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.		Use ISRU principles to educate, inspire and motivate
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.		Utilize nuclear power for ISRU systems

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 2nd 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?