NASA Technology Roadmaps Study
Aeronautics and Space Engineering Board, National Research Council
Human Health and Surface Exploration Panel
WORKSHOP

NASA Office of Chief Technologist Space Technology Roadmap Technology Area 07 Human Exploration Destination Systems

Kriss J. Kennedy, Chair

Team Members:

Leslie Alexander

Mike Lowry (*Rob Landis*)

Diane Linne

Carole Mclemore

Edgardo Santiago-Maldonado

Technology Coordinator: David L. Brown

Support Team Members:

Peter Curreri

Peggy Guirgis

John Sims

Michael Tinker

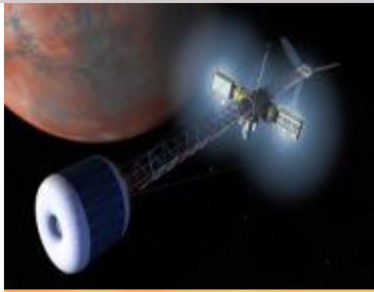
Brian Johnson

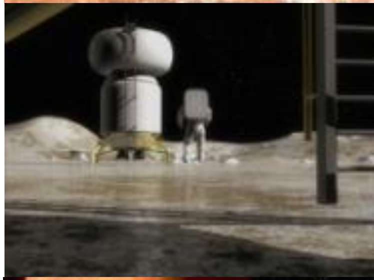
OCT Technology POC: Dr. Howard Ross

27 April 2011

Briefing Package Contents

- OCT & TA07 Process
- TA07 HEDS Overview & Framework
- Top Technical Challenges
- Facility Needs Summary
- Level-1 and Level-2 Roadmaps
- State-of-the-Art, Current TRLs
- Appendices
  - Technology Dependencies
  - Impact to National Needs





TA07 Human Exploration Destination Systems

Executive Summary

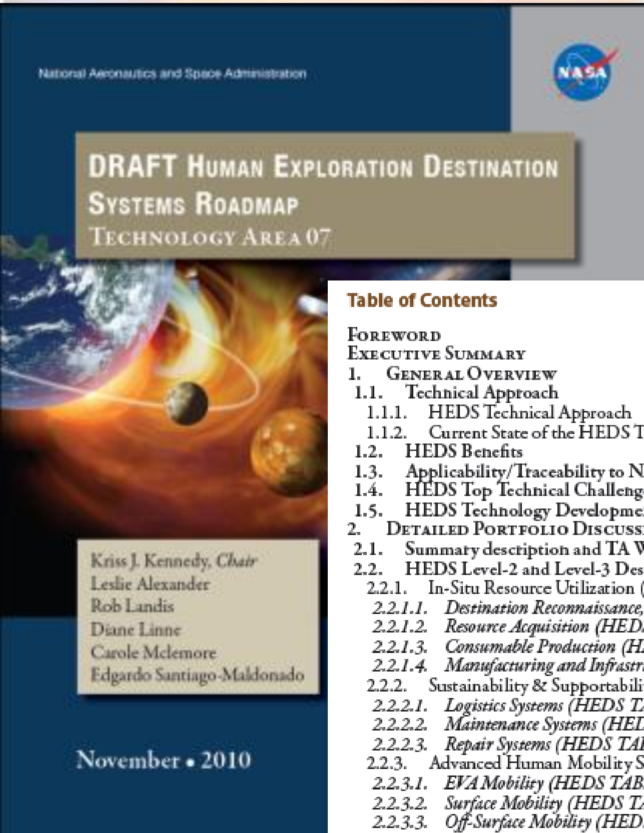


Table of Contents

- **I ASSUME everyone has read the TA7 Draft Roadmap Report!** *30-page Report*
- ***Strategic Capabilities Roadmap***
- **Exploration capabilities matured by "applied" technology investments**
- **Level-1 Roadmap**
- **Level-2 Roadmaps** *(not in report, in briefings)*
- **Technology Level 4 & 5 in spreadsheet**
- **Mission Pull Capabilities**
- **Mission Push Capabilities**
- **TRLs and Facilities**
- **Mapped Dependencies on other technology areas**
- **Mapped impacts to National Needs**
- **Out-of-Scope to ID "what is funded"**

TA07 Roadmap Definition Process

Select Team Of Experts → Develop Work Breakdown Structure → Develop Roadmap → Other TA Implications → Agency Review

Select Team Of Experts

TA7 HEDS Experts Across Agency:

- Howard Ross- HQ
- Kriss Kennedy - JSC
- Leslie Alexander - MSFC
- Michael Lowry - ARC
- *Rob Landis - ARC*
- Diane Linne - GRC
- Carole Mclemore - MSFC
- Edgardo Santiago-Maldonado - KSC
- David L. Brown - JSC
- Peter Curreri - MSFC
- Peggy Guirgis - JSC
- Michael Tinker - MSFC
- Tu-Quynh Bui – JSC
- Brian Johnson – JSC
- John Sims – JSC

Develop Work Breakdown Structure

- Develop Drivers
  - “Pull”: NASA Future Destination Architecture; HEFT, NRC Decadal Surveys
  - “Push”: Capabilities; Game Changing; Lower Cost; increased autonomy
- Define Top Level HEDS Technology Challenges
- Develop First Level WBS Sub elements
- Assign Team Leads for each sub-element
- Define Technology Challenges for each Sub-element
- Further WBS Breakdown of each WBS sub-element

Develop Roadmap

- Reviewed previous roadmaps
- Targeted Capabilities in NASA Road-map first
- Consulted with other experts to determine technology development timelines.
- Assumed no funding constraints
- Included demo flights prior to operational use.

Other TA Implications

- Identified TA dependencies & collaborations
- Mapped to National Needs

Agency Review

- Draft Roadmaps
- NASA-wide review from all Technology Areas
- RID Process
- Direct contact with RID author to close RID

Human Exploration Destination Systems Technology Area

Vision

To enable a sustained human presence for exploring destinations such as remote sites on Earth and beyond including, but not limited to, Low Earth Orbit (LEO), High Earth Orbit (HEO), Geosynchronous Orbit (GEO), Near Earth Object (NEO), and the vicinity of Mars and beyond.

Mission

To strategically guide NASA and the U.S. Government agencies' technology investments that will result in capabilities enabling human exploration missions to various destinations.

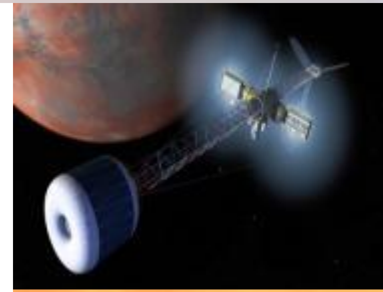
Goals

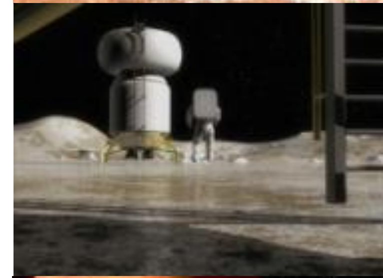
- To guide NASA and the government's technology investments for the next 20 years
- To roadmap innovative and cross-cutting technologies that offer game-changing and revolutionary benefits to enable affordable and sustainable space exploration missions
- To guide technology demonstrations
- To re-invigorate the nation's technological prowess
- To encourage commercial development of space
- To inspire students to pursue STEM curricula
- To renew the American public's enthusiasm, interest and excitement for the space program

Objectives

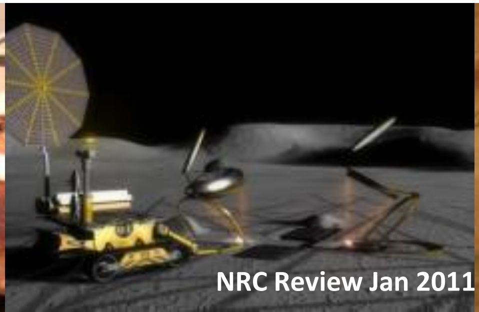
- To understand past technology roadmaps
- To look across multiple agencies for common issues and technology investments for opportunities of collaboration
- To engage commercial industry
- To engage academia
- To define the potential technology benefits in terms of science and everyday life
- To create and deliver a HEDS Area Roadmap and TABS to OCT that identifies significant capability improvements
- To provide a report that describes the HEDS A-STAR Roadmap and TABS
- To support NASA and NRC peer reviews

Traceability to NASA Strategic Goals



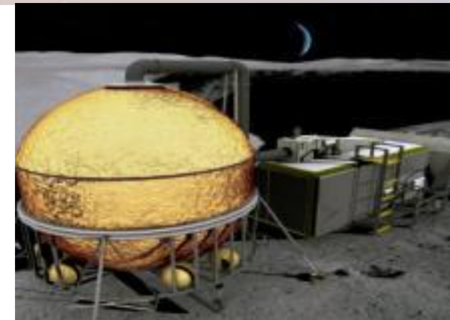



- ✓**Energize** competitive domestic industries
- ✓**Expand** international cooperation
- ✓**Strengthen** stability in space
- ✓**Increase** assurance and resilience of mission-essential functions
- ✓**Pursue** human and robotic initiatives
- ✓**Improve** space-based Earth and solar observation

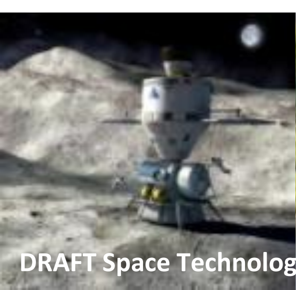
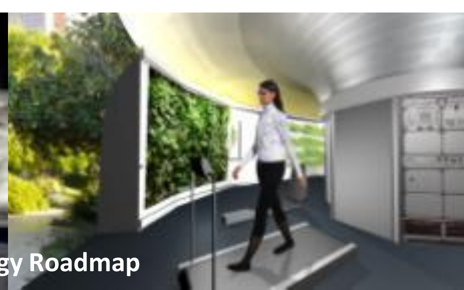




TA7 Capability Benefits

- ✓**Revolutionizes** architectures and mission planning
- ✓Guides **identification** of human accessible targets
- ✓**Increases** crew productivity and science return
- ✓**Reduces** launch and mission costs, and increases crew safety
- ✓**Enables** commercial spin-offs
- ✓**Cultivates** commercialization and development of LEO
- ✓**Promotes** STEM careers





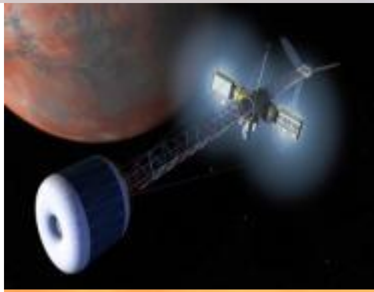

Human Exploration Destination Systems Technology Area Overview

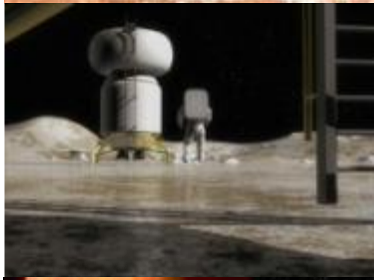
TA07 Human Exploration Destination Systems

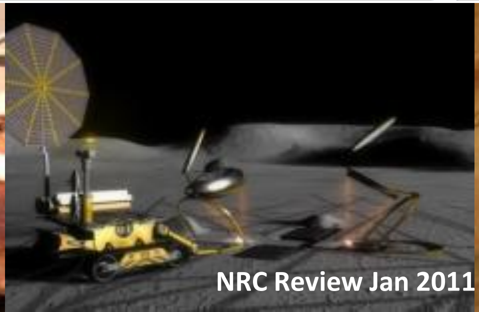
- 7.1 In-Situ Resource Utilization
- 7.2 Sustainability & Supportability
- 7.3 “Advanced” Human Mobility Systems
- 7.4 “Advanced” Habitat Systems
- 7.5 Mission Operations & Safety
- 7.6 Cross-Cutting Systems

Traceability to NASA Mission Directorate Interests

TA7: Human Exploration Destination Systems		SMD	SOMD	ARMD	ESMD
7.1 In-Situ Resource Utilization	This area covers the identification, acquisition, and utilization of in situ resources including natural and man-made.	X	X	X	X
7.2 Sustainability & Supportability	This area covers operations and the sustainability of humans and required vehicles and systems.	X	X	X	X
7.3 Advanced Human Mobility Systems	This area covers the transportation or mobility of humans and cargo in the near proximity of the destination or on the surface .		X	X	X
7.4 Advanced Habitat Systems	This area covers advanced habitat technologies of deep space habitat capabilities that enable long-duration and deep-space human missions.		X		X
7.5 Mission Operations & Safety	This area covers the safety and health of humans, vehicles, systems, and destinations.	X	X	X	X
7.6 Cross-Cutting Systems	This area covers the identification and characterization of destination targets, systems engineering, and technologies for construction, assembly, and deployment of destination systems hardware.	X	X	X	X






Human Exploration Destination Systems

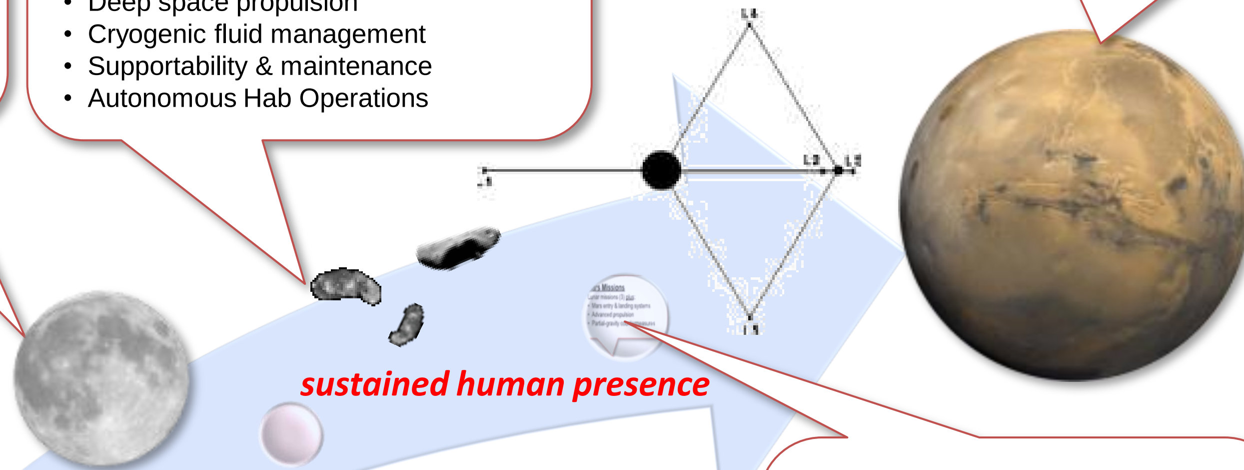
a sustained human presence

Lunar Missions
lunar orbit, lunar surface
- Landing systems
- Nuclear power
- In-situ resource utilization
- Surface Habitation
- Autonomous Operations
- Surface Rover
- Surface EVA mobility

Deep Space
LaGrange Points, NEOs and beyond
- Crew support for 30-60 + days (habitat)
- Radiation protection (habitat)
- Life support (habitat)
- Deep space propulsion
- Cryogenic fluid management
- Supportability & maintenance
- Autonomous Hab Operations

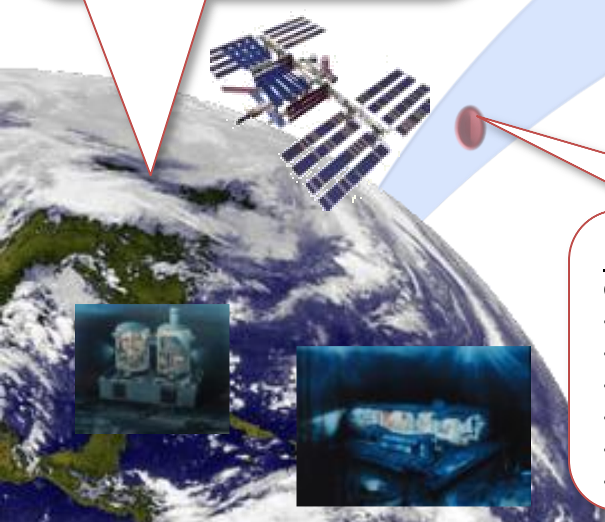
Mars Missions
Lunar missions plus:
- Mars entry & landing systems
- Advanced propulsion
- Partial-gravity countermeasures

Remote Earth Destinations
Antarctica, Deep-Water
- Analogs
- Operations Concept Validation
- Science & Mission Ops
- Autonomous Hab Operations
- Hardware/Software Demos
- Closed-loop life support
- Inflatable Hab Demos
- Environmental monitoring
- Supportability & Maintenance



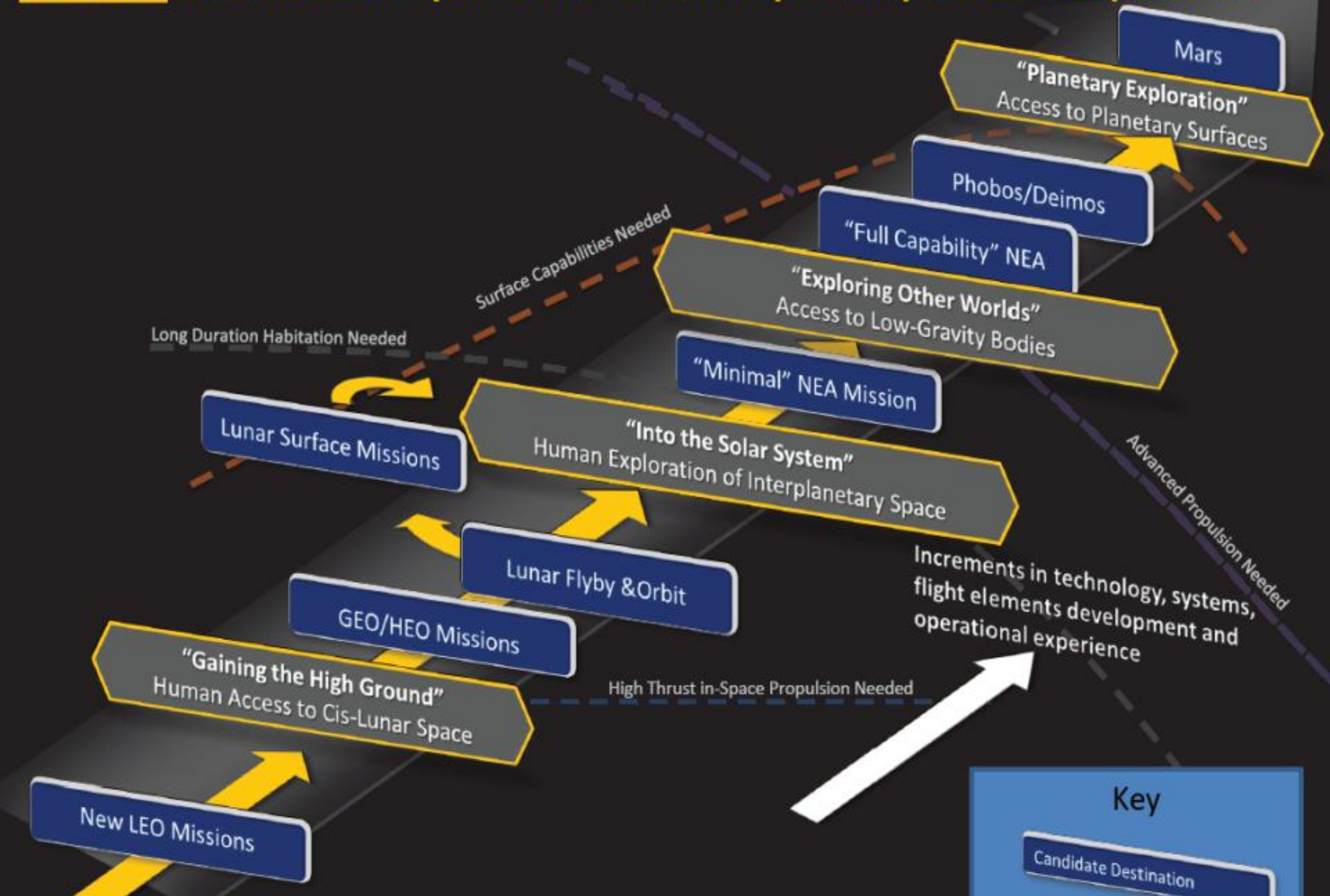
Interplanetary Transportation
LEO to Destinations
- Heavy lift launch
- Autonomous Hab Operations
- Inflatable Module
- Closed-loop life support
- Crew support for long-duration flights
- Deep-space propulsion
- Radiation protection

Near-Earth Space
HEO, lunar orbit, Libration Points
- Heavy lift launch
- Autonomous Hab Operations
- Inflatable Hab Module
- Closed-loop life support
- Crew support for - 20 days
- Deep-space propulsion
- Radiation protection

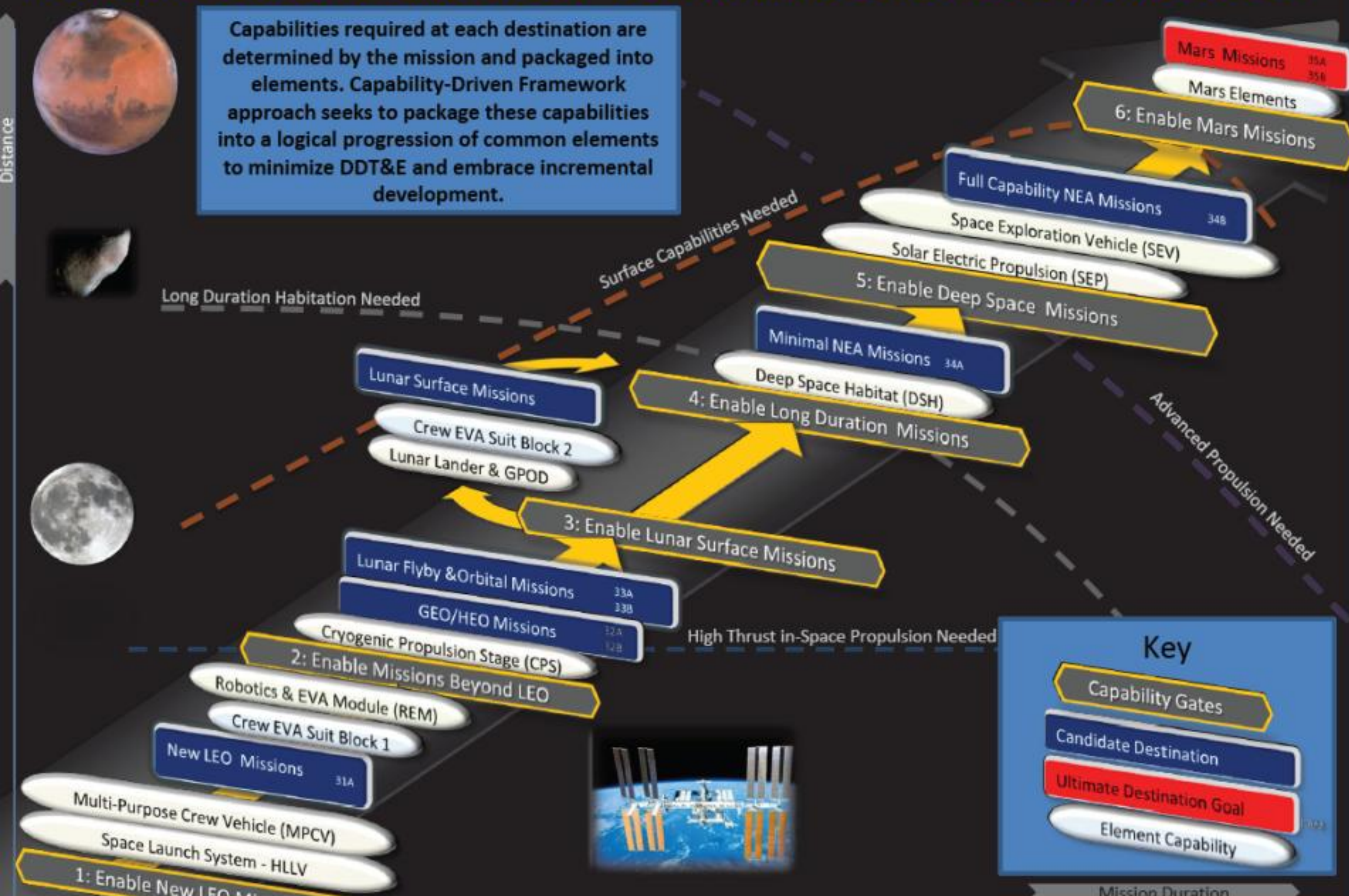


Low-Earth Orbit
Commercialization
- Zero-g research platform
- Autonomous Hab Operations
- Inflatable Hab Module
- Closed-loop life support
- Environmental monitoring
- Supportability & Maintenance concepts

Notional Incremental Expansion of Human Space Exploration Capabilities



INCREMENTAL EXPANSION OF HUMAN EXPLORATION CAPABILITIES



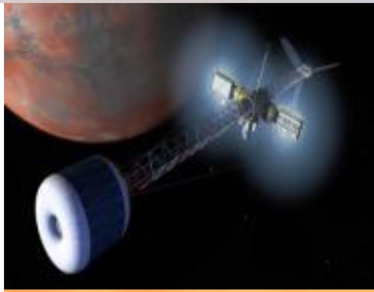
Human Exploration Destination Systems

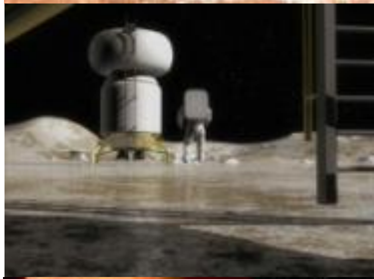
a sustained human presence

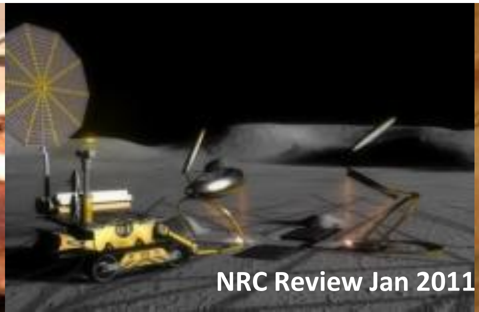
HEDS Technologies Enable	Destination Systems Capability Needs
• Sustained human presence in space including planetary bodies • Remote Earth analog destinations and research • Commercialization of LEO destinations • Development of GEO & LaGrange point destinations • Inter-Planetary space transportation (spacecraft) to destinations • Exploration of NEO destinations • Exploration of surface destinations	• Launch & Propulsion Systems (TA01, TA02, TA09, TA13) • Habitat Systems (TA06, TA07, TA12) • Laboratory Systems (Geo-Sciences, Physical Sciences, Life Sciences) (TA06, TA07, TA08) • Mobility Systems (TA04, TA07) • Autonomous & Intelligent Operations (TA04, TA07, TA11) • Power Generation & Stowage (TA03) • Communication Systems (TA05) • Thermal Systems (TA14) • ISRU Systems (TA07) • Logistics Systems (TA07) • Manufacturing & Repair Systems (TA07, TA10, TA11, TA12) • Bio-Technology Systems (TA06, TA07, TA10) • Artificial-Gravity Systems (TA06, TA07) • Medical Systems (TA06, TA08)

HEDS Push - Pull Mission Approach

- ‘**Pull**’ missions identified by NASA Mission Directorates, architecture teams
- Additional ‘**Push**’ missions added by HEDS team to facilitate our key objectives and needs
    - Sustainable exploration
    - NEO identification
    - Commercialization

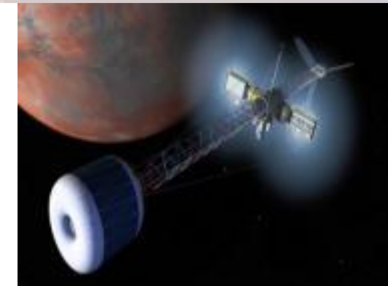




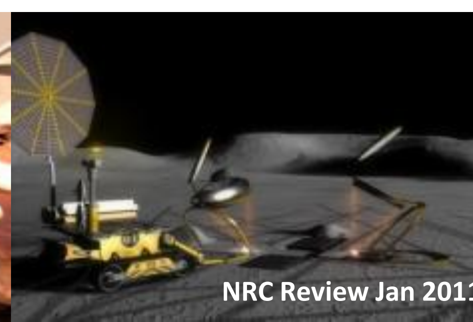




Determination of Technology Need Date

- Need to be at **TRL 6** by element or system **PDR**
  - 3-4 years before launch for **robotic mission**
  - 5-6 years before launch for **crewed mission**
- True '**game-changing**' technologies need to be at or near TRL 6 at the beginning of mission architecture development
- This **philosophy** was key in creation of 'push' missions






Top TA07 Technical Challenges

2010-2016:

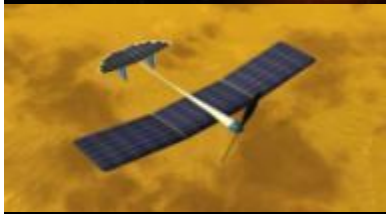
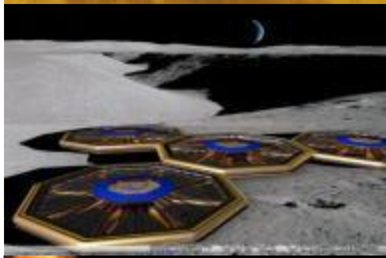
- Suitports, suitlocks, & alternative airlock systems
- Advanced materials and processes to enable in-situ repair
- Development of crew autonomy and autonomous spacecraft concepts
- In Situ Resource Acquisition Technologies

2017-2022:

- Radiation protection technologies
- Technologies to minimize mass of cargo and logistic needs from Earth
- Advances in "smart" Habs Technologies
- Advances and increases crew autonomy
- Advances in Hab integrated shell technologies
- Solids and fluids processing technologies

2023-2028:

- Technologies to enable reconfigurability and reusability of components and subsystems
- Large scale dust removal and mitigation
- In situ manufacturing and infrastructure technologies

TA07 Facility Needs

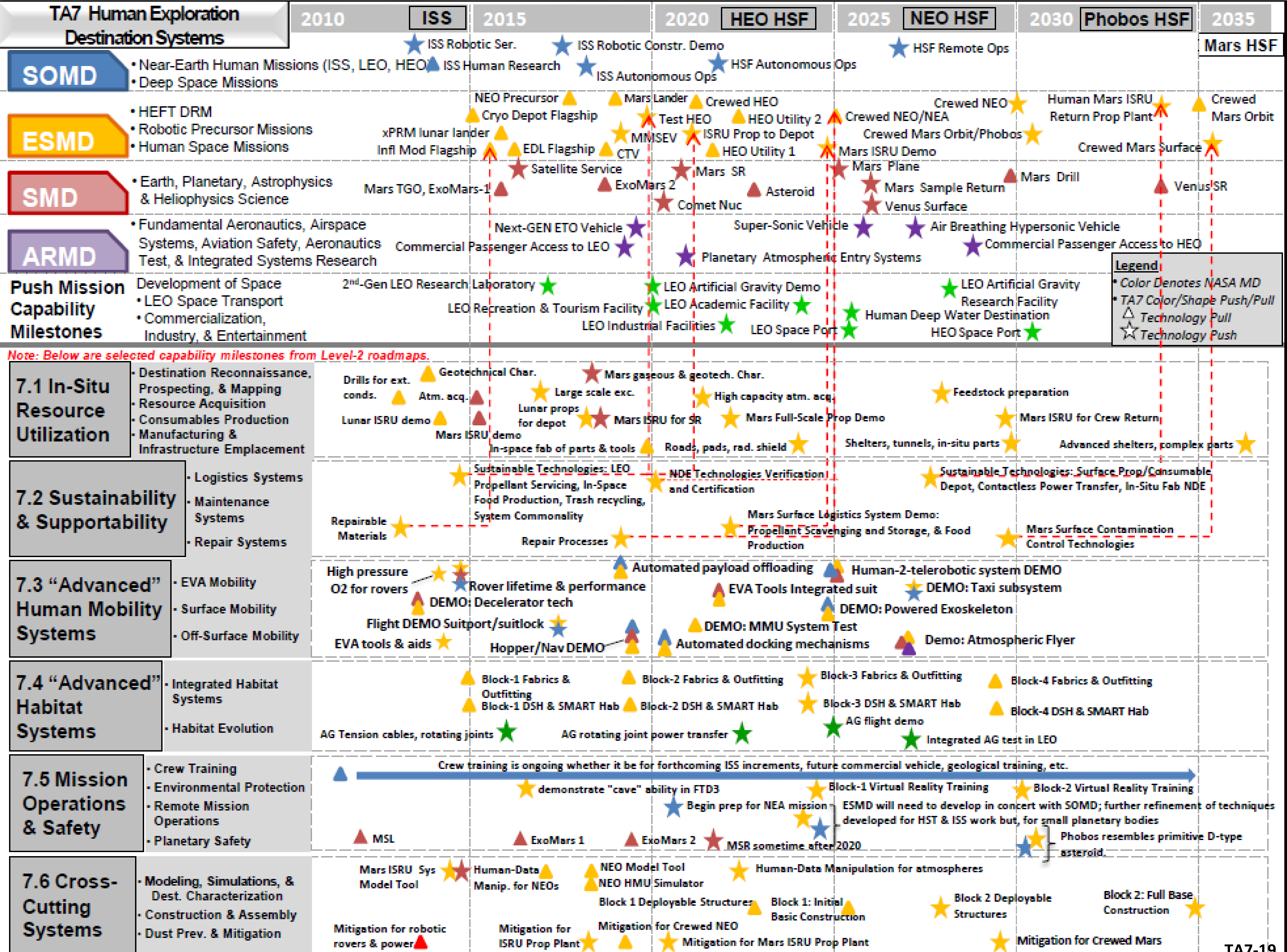
Applicable across TA07. Specific testing timeframe and facilities requirements are the technology project implementation responsibility

- **Space Environment Testing Chambers**
  - EMI, corona, thermal, vacuum, radiation, atomic O2, MM-OD, UV, etc
  - Thermal-Vacuum Chambers (small, medium and large size)
- **Special Thermal-Vac Dust Testing Chambers-Dirty Chambers** (Simulate Moon and Mars)
- **Space Radiation Testing Labs**
- **Hypervelocity Impact Lab (WSTF)**
- **Integrated Testbeds (Avionics, systems and software)**
- **Simulants Development Lab/Facility**
- **Acoustics Testing Chamber/Lab**
- **Vibration Testing Chamber/Lab**
- **Material Toxicity Testing Chambers**
- **6-DOF and Air-bearing Floor Facility**
- **Virtual Reality Lab, Training & Flight Simulators**
- **Sample Return Processing and Curation Facility** (Asteroid, Moon, Mars)
- **Parabolic Flight Testing**
- **Analogs** (D-RaTS, NEEMO, Antarctica, etc)
- **Human-Rated Test Chamber for reduced psi @ elevated O2 (e.g. JSC 20' chamber)**
- **International Space Station**
- **Other National Labs**
- **Other Orbital Space Facilities**

Technology Area Breakdown Structure

TA07 Human Exploration Destination Systems

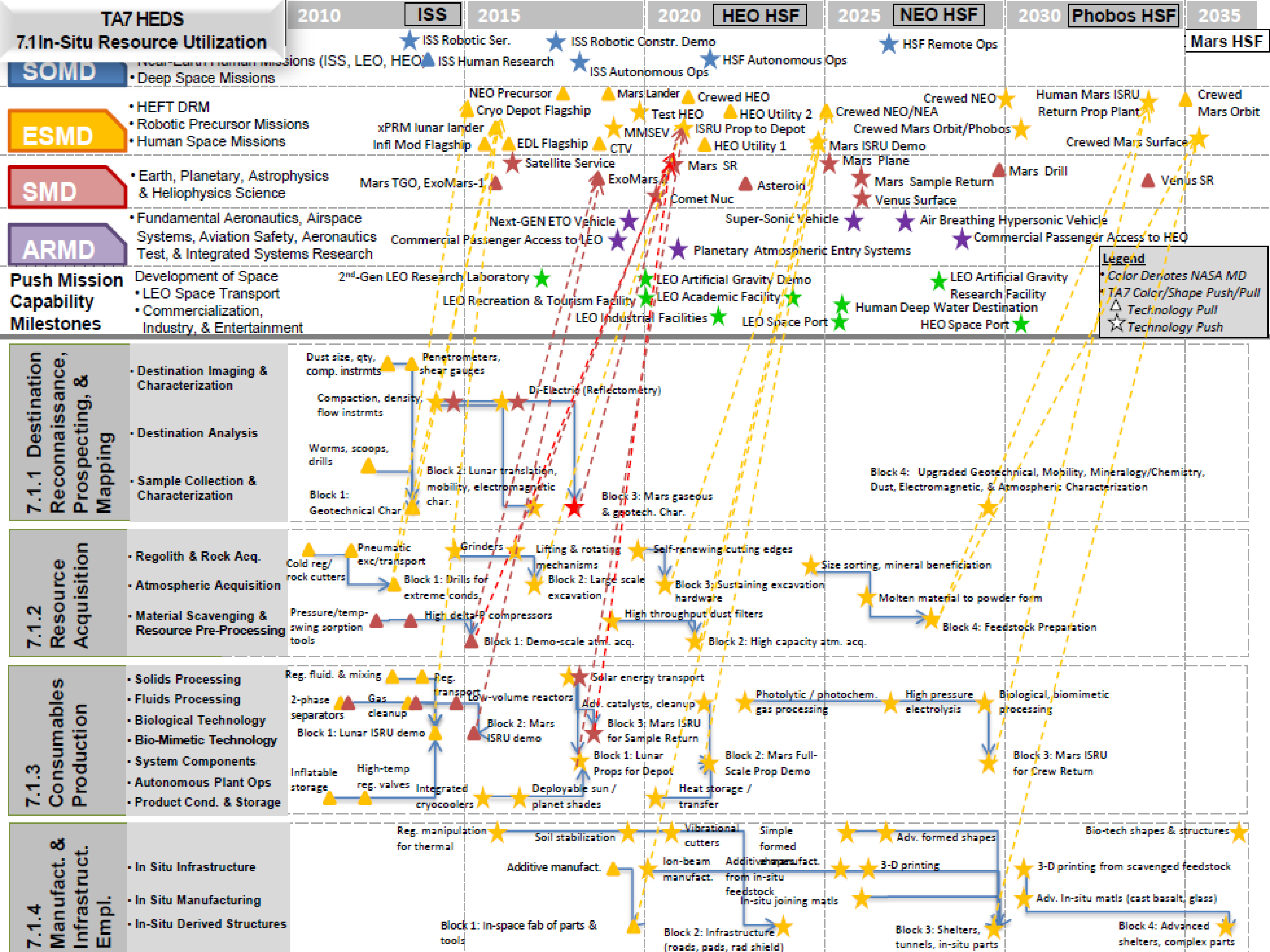
- **7.1 In-Situ Resource Utilization**
  - 7.1.1 Destination Reconnaissance, Prospecting, & Mapping
  - 7.1.2 Resource Acquisition
  - 7.1.3 Consumables Production
  - 7.1.4 Manufacturing & Infrastructure Emplacement
- **7.2 Sustainability & Supportability**
  - 7.2.1 Logistics Systems
  - 7.2.2 Maintenance Systems
  - 7.2.3 Repair Systems
- **7.3 "Advanced" Human Mobility Systems**
  - 7.3.1 EVA Mobility
  - 7.3.2 Surface Mobility
  - 7.3.3 Off-Surface Mobility
- **7.4 "Advanced" Habitat Systems**
  - 7.4.1 Integrated Habitat Systems
  - 7.4.2 Habitat Evolution
- **7.5 Mission Operations & Safety**
  - 7.5.1 Crew Training
  - 7.5.2 Environmental Protection
  - 7.5.3 Remote Mission Operations
  - 7.5.4 Planetary Safety
- **7.6 Cross-Cutting Systems**
  - 7.6.1 Modeling, Simulations, & Destination Characterization
  - 7.6.2 Construction & Assembly
  - 7.6.3 Dust Prevention & Mitigation



TA7 Human Exploration Destination Systems
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
Test HEO
MMSEV
CTV
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO
Crewed NEO/NEA
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Human Mars ISRU Return Prop Plant
Crewed Mars Orbit
Crewed Mars Surface
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Super-Sonic Vehicle
Planetary Atmospheric Entry Systems
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
LEO Artificial Gravity Research Facility
Human Deep Water Destination
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
Note: Below are selected capability milestones from Level-2 roadmaps.
7.1 In-Situ Resource Utilization
• Destination Reconnaissance, Prospecting, & Mapping
• Resource Acquisition
• Consumables Production
• Manufacturing & Infrastructure Emplacement
Drills for ext. conds.
Atm. acq.
Lunar ISRU demo
Mars ISRU demo
Geotechnical Char.
Lunar props for depot
Large scale exc.
Mars gaseous & geotech. Char.
Mars ISRU for SR
In-space fab of parts & tools
High capacity atm. acq.
Mars Full-Scale Prop Demo
Roads, pads, rad. shield
Feedstock preparation
Mars ISRU for Crew Return
Shelters, tunnels, in-situ parts
Advanced shelters, complex parts
7.2 Sustainability & Supportability
• Logistics Systems
• Maintenance Systems
• Repair Systems
Repairable Materials
Sustainable Technologies: LEO Propellant Servicing, In-Space Food Production, Trash recycling, System Commonality
Repair Processes
NDE Technologies Verification and Certification
Mars Surface Logistics System Demo: Propellant Scavenging and Storage, & Food Production
Sustainable Technologies: Surface Prop/Consumable Depot, Contactless Power Transfer, In-Situ Fab NDE
Mars Surface Contamination Control Technologies
7.3 "Advanced" Human Mobility Systems
• EVA Mobility
• Surface Mobility
• Off-Surface Mobility
High pressure O2 for rovers
Rover lifetime & performance
DEMO: Decelerator tech
Flight DEMO Suitport/suitlock
EVA tools & aids
Hopper/Nav DEMO
Automated payload offloading
EVA Tools Integrated suit
DEMO: MMU System Test
Automated docking mechanisms
Human-2-telerobotic system DEMO
DEMO: Taxi subsystem
DEMO: Powered Exoskeleton
Demo: Atmospheric Flyer
7.4 "Advanced" Habitat Systems
• Integrated Habitat Systems
• Habitat Evolution
Block-1 Fabrics & Outfitting
Block-1 DSH & SMART Hab
AG Tension cables, rotating joints
Block-2 Fabrics & Outfitting
Block-2 DSH & SMART Hab
AG rotating joint power transfer
Block-3 Fabrics & Outfitting
Block-3 DSH & SMART Hab
AG flight demo
Integrated AG test in LEO
Block-4 Fabrics & Outfitting
Block-4 DSH & SMART Hab
7.5 Mission Operations & Safety
• Crew Training
• Environmental Protection
• Remote Mission Operations
• Planetary Safety
Crew training is ongoing whether it be for forthcoming ISS increments, future commercial vehicle, geological training, etc.
demonstrate "cave" ability in FTD3
Begin prep for NEA mission
Block-1 Virtual Reality Training
Block-2 Virtual Reality Training
ESMD will need to develop in concert with SOMD; further refinement of techniques developed for HST & ISS work but, for small planetary bodies
Phobos resembles primitive D-type asteroid.
MSL
ExoMars 1
ExoMars 2
MSR sometime after 2020
7.6 Cross-Cutting Systems
• Modeling, Simulations, & Dest. Characterization
• Construction & Assembly
• Dust Prev. & Mitigation
Mars ISRU Sys Model Tool
Human-Data Manip. for NEOs
NEO Model Tool
NEO HMU Simulator
Human-Data Manipulation for atmospheres
Block 1 Deployable Structures
Block 1: Initial Basic Construction
Block 2 Deployable Structures
Block 2: Full Base Construction
Mitigation for robotic rovers & power
Mitigation for ISRU Prop Plant
Mitigation for Crewed NEO
Mitigation for Mars ISRU Prop Plant
Mitigation for Crewed Mars

TA7 HEDS In-Situ Resource Utilization

- **7.1 In-Situ Resource Utilization**
  - 7.1.1 Destination Reconnaissance, Prospecting, & Mapping
    - 7.1.1.1 Destination Imaging & Characterization
    - 7.1.1.2 Destination Analysis
    - 7.1.1.3 Sample Collection & Characterization
  - 7.1.2 Resource Acquisition
    - 7.1.2.1 Regolith & Rock Acquisition
    - 7.1.2.2 Atmospheric Acquisition
    - 7.1.2.3 Material Scavenging & Resource Pre-Processing
  - 7.1.3 Consumables Production
    - 7.1.3.1 Solids Processing
    - 7.1.3.2 Fluids Processing
    - 7.1.3.3 Biological Technology
    - 7.1.3.4 Bio-mimetic Technology
    - 7.1.3.5 System Components
    - 7.1.3.6 Autonomous Plant Operations
    - 7.1.3.7 Product Conditioning & Storage
  - 7.1.4 Manufacturing & Infrastructure Emplacement
    - 7.1.4.1 In-Situ Infrastructure
    - 7.1.4.2 In-Situ Manufacturing
    - 7.1.4.3 In-Situ Derived Structures



TA7 HEDS
7.1 In-Situ Resource Utilization
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
CTV
MMSEV
Mars Lander
Test HEO
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO/NEA
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Crewed NEO
Human Mars ISRU Return Prop Plant
Crewed Mars Orbit
Crewed Mars Surface
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars-2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
Human Deep Water Destination
LEO Artificial Gravity Research Facility
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
7.1.1 Destination Reconnaissance, Prospecting, & Mapping
• Destination Imaging & Characterization
• Destination Analysis
• Sample Collection & Characterization
Dust size, qty, comp. instrmts
Penetrometers, shear gauges
Compaction, density, flow instrmts
Di-Electric (Reflectometry)
Worms, scoops, drills
Block 1: Geotechnical Char
Block 2: Lunar translation, mobility, electromagnetic char.
Block 3: Mars gaseous & geotech. Char.
Block 4: Upgraded Geotechnical, Mobility, Mineralogy/Chemistry, Dust, Electromagnetic, & Atmospheric Characterization
7.1.2 Resource Acquisition
• Regolith & Rock Acq.
• Atmospheric Acquisition
• Material Scavenging & Resource Pre-Processing
Cold reg/ rock cutters
Pneumatic exc/transport
Block 1: Drills for extreme conds.
Grinders
Lifting & rotating mechanisms
Block 2: Large scale excavation
Self-renewing cutting edges
Block 3: Sustaining excavation hardware
Size sorting, mineral beneficiation
Molten material to powder form
Block 4: Feedstock Preparation
Pressure/temp-swing sorption tools
High delta-P compressors
Block 1: Demo-scale atm. acq.
High throughput dust filters
Block 2: High capacity atm. acq.
7.1.3 Consumables Production
• Solids Processing
• Fluids Processing
• Biological Technology
• Bio-Mimetic Technology
• System Components
• Autonomous Plant Ops
• Product Cond. & Storage
Reg. fluid. & mixing
Reg. transport
2-phase separators
Gas cleanup
Block 1: Lunar ISRU demo
Low-volume reactors
Block 2: Mars ISRU demo
Solar energy transport
Adv. catalysts, cleanup
Block 3: Mars ISRU for Sample Return
Block 1: Lunar Props for Depot
Photolytic / photochem. gas processing
High pressure electrolysis
Biological, biomimetic processing
Block 2: Mars Full-Scale Prop Demo
Block 3: Mars ISRU for Crew Return
Inflatable storage
High-temp reg. valves
Integrated cryocoolers
Deployable sun / planet shades
Heat storage / transfer
7.1.4 Manufact. & Infrastruct. Empl.
• In Situ Infrastructure
• In Situ Manufacturing
• In-Situ Derived Structures
Reg. manipulation for thermal
Soil stabilization
Additive manufact.
Block 1: In-space fab of parts & tools
Vibrational cutters
Ion-beam manufact.
Simple formed shapes
Additive manufact. from in-situ feedstock
In-situ joining matls
Block 2: Infrastructure (roads, pads, rad shield)
Adv. formed shapes
3-D printing
Block 3: Shelters, tunnels, in-situ parts
Bio-tech shapes & structures
3-D printing from scavenged feedstock
Adv. In-situ matls (cast basalt, glass)
Block 4: Advanced shelters, complex parts

"Path-to-TRL-6" Matrix

- Below is an *example* of the excel "Path-to-TRL-6" Matrix
- Only first 3 columns are shown in this briefing
- A work-in-progress—not complete.
- Will be holding "TRL Validation TIMs" with SME and personnel
- Use this matrix along with the breakdown structure and roadmaps to determine time to mature capabilities—driven by DRM need & Concept of Operations
- Does not ID funded/not funded by NASA, other agencies, nor industry

first 3 columns

			Function	Current State-of-the-Art / Practice	Current TRL	Major Challenge(s)	Milestones/Activities to Advance to TRL 6 or beyond	Key Performance Parameters	Facility Needs
TA7: Human Exploration Destination Systems									
	7.1 In-Situ Resource Utilization	This area covers the identification, acquisition, and utilization of in situ resources							
		7.1.1	Destination Reconnaissance, Prospecting, & Mapping						
		7.1.1.1	Destination Imaging & Characterization	Lunar and Mars Reconnaissance Orbiters, Rosetta and Deep Impact Asteroid Missions - LCROSS had detection limits (for example could not detect chlorine) - the ILWEAG did a very thorough/detailed analysis of all the instruments and where they stand, etc. Also the MEPAG may have done a similar exercise (same for the other 2 sub-elements here)	TRL 3 - 5	Although many missions have achieved broad scientific analysis, more specific characterization instruments are needed to identify resource-rich areas for ISRU. Also need information for beneath the surface. Some possibilities include: - lawn dart penetrator - drop it from orbit to give information from under the surface remotely - near-infrared spectrometer with new detector based on data gained from LCROSS; saw components they didn't expect; need to refine so it hits different/refined spectral range; - this takes you back from a TRL 9 for what was flown back to TRL 3 - 4 - atomic adsorption spectroscopy - lasers to excite the material and	Lunar Geotechnical Characterization, Lunar Polar Ice characterization, Mars gaseous, ice and dust, and geotech characterization	Commercial grade resource survey of outpost sites.	- Space Environment Testing Chambers - EMI, corona, thermal, vacuum, radiation, atomic O2, MM-OD, UV, etc - Thermal-Vacuum Chambers (small, medium and large size) - Special Dust Testing Chambers (Moon and Mars) - Space Radiation Testing Labs - Vibration Testing Chamber/Lab - Virtual Reality Lab, Training & Flight Simulators - Sample Return (Asteroid, Moon, Mars) Processing and Curation Facility - Analogs (D-RaTS, NEEMO, Antarctica, etc)

7.1 In-Situ Resource Utilization

7.1.1 Destination Reconnaissance, Prospecting, & Mapping	Current State-of-the-Art Practice	Current TRL
Destination Imaging & Characterization	Lunar and Mars Reconnaissance Orbiters, Rosetta and Deep Impact Asteroid Missions - LCROSS had detection limits (for example could not detect chlorine) - the ILWEAG did a very thorough/detailed analysis of all the instruments and where they stand, etc. Also the MEPAG may have done a similar exercise (same for the other 2 sub-elements here)	**TRL 3 - 5**
Destination Analysis	Lunar Surveyor Program, Mars Exploration Rovers	**TRL 4-5**
Sample Collection and Characterization	Apollo Missions lunar sample characterization. Mars Rovers with soil characterization . Asteroid missions. -No lunar polar samples have been taken or returned. -Limited in-situ analysis but no sample return from Mars has been achieved - Very limited cometary dust samples and very limited asteroid in-situ characterization and no samples have been returned.	**TRL 4**

7.1 In-Situ Resource Utilization

7.1.2 Resource Acquisition	Current State-of-the-Art Practice	Current TRL
Regolith and Rock Acquisition	Lunar Sample collection and return and Apollo sample collection and return missions - Continuous excavation operation demonstrated in labs and field demos: 10's to 100's of minutes - No full excavation tests in simulated lunar/planetary environment (vacuum, temp extremes, geotechnical simulant) - Semiautonomous robotic mining has now been implemented at production scale on Earth. TRL depends what body we are going to be on: - for Mars, MSL will be high TRL going to very small depth (5 cm) and small samples, but lower TRL for deeper digging and/or larger quantities - NEOs is much lower since we know much less about the regolith; maybe TRL 2 max for larger acquisition that would be needed for resource processing, - for lunar, did in Apollo, but those folks are not around and we need to go deeper, dig up more for ISRU, so maybe TRL 4	**TRL 2 - 4**
Atmospheric Acquisition	Laboratory demonstrations, Earth based production of gases. -**very** small-scale flight hardware flight qualified but never flown (12-yr old tech.) -cold finger collection of CO_2 has been done - in a lab - Pioneer did in a Mars pressure environment - but very little work on cycling and system (freeze, release, capture, start over) - Mars Technology Program developing technologies for sample return are also looking at acquiring atmospheric samples - molecular sieve TRL 4 - have been using these for a long time but maybe not in simulated Mars atmosphere	**TRL 3 - 4**
Material Scavenging and Resource Pre-Processing	Earth based recycling programs	**TRL 2 - 4**

7.1 In-Situ Resource Utilization

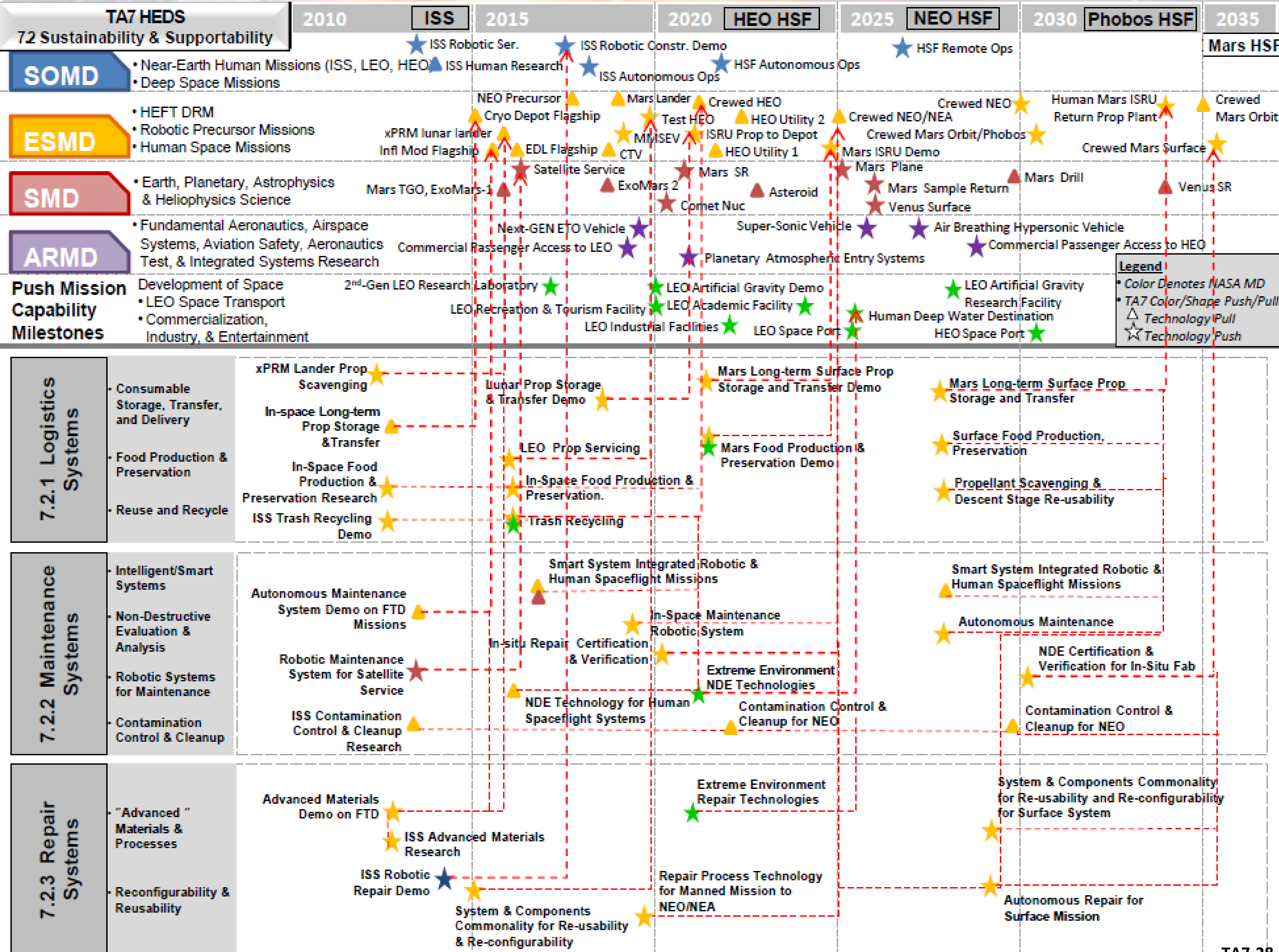
7.1.3 Consumables Production	Current State-of-the-Art Practice	Current TRL
Solids Processing	Ground based short term oxygen and metals extraction from lunar and Mars simulants. - Hydrogen reduction of local material at field demo had system mass 2.6 times the mass of O2 that could have been produced in a year (if operated that long) - Total hours of operation of a system demonstrated in field demo is 20 hrs -Carbothermal reduction system demonstrated at field demo at scale for making 1000 kg O2/year - Molten oxide electrolysis single batch at lab scale - some pneumatic transfer work in a vacuum (Honeybee) - some auger transfer at low pressures (Orbitec)	**TRL 3 - 4**
Fluids Processing	ISS fluid science experiments and life support systems; electrolysis systems flown on station Ground based short term oxygen and metals extractions from lunar and Mars simulants included downstream systems to complete oxygen extraction process: - water electrolysis - Sabatier reaction to form methane - reverse water gas shift - water and gas clean-up	**TRL 4-5**
Biological technology	ISS Microgravity Experiments Mining industry on earth uses bacteria (extremophiles) that process sulfides as a production process - some folks at JSC/Ames have used cyanobacteria - for using this for resources on moon, mars, etc., probably at TRL 1 - 2 - we know it can happen but haven't really been working on it much; also have to tailor it to our specific compounds	**TRL 1 - 2**
Bio-mimetic technology	ISS Measurement Systems	**TRL 1 - 2**
System Components	Laboratory demonstrations, Earth based tests at analog sites. - doing some seals and bearings tests with regolith but not under vacuum yet (TRL 4) - did some limited vacuum testing under Dust program, but probably not enough to raise to TRL 5 yet	**TRL 3 - 4**
Autonomous Plant Operations	Earth based Plants and systems - while there are autonomous systems used in chemical industry, probably still at a TRL 4 max for systems for ISRU plants that operate in hostile environments with time delays. Theory is definitely there. - terrestrial solution for jams with powdered media is to go out and 'kick the machine'	**TRL 3-4**
Product Conditioning and Storage	Earth based Plants and systems, CRYOSTAT orbital demonstration. - inflatable water bags used on shuttle/station (standard temp and pressure)	**TRL 3 - 5**

7.1 In-Situ Resource Utilization

7.1.4 Manufacturing & Infrastructure Emplacement	Current State-of-the-Art Practice	Current TRL
In Situ Infrastructure	Laboratory demonstrations - 8 to 10 cm excavation depth in uncompacted simulant in vacuum (very small scale - reproduction of surveyor excavation) - 120 cm berm height demonstrated in air with marginal geotechnical simulant and over-sized (mass) equipment -At small scale, it is high TRL (Apollo dug with shovels, etc., duplication of surveyor) - for scale we need here, it is still lower TRL because we haven't taken anything of scale we need into the vacuum environment, compaction, etc. - what has been done is more at component level (i.e., just the digging tool) and not the integrated vehicle, force interactions	**TRL 3 - 4**
In Situ Manufacturing	-lab analogs with commercially processed materials - feasibility studies with simulants (someone literally melted lunar material and made an obsidian like material but never made anything with it - low TRL for making from natural resources (i.e., regolith) maybe TRL 2 - K. Taminger's free-form fabrication device was about ready to go on station (higher, maybe TRL 6). Unfortunately need post-processing (machine shop); FFF methods that don't need post-processing are still low (TRL 3 - 4 or less for ion technologies)	**TRL 2 - 4**
In-Situ Derived Structures	-water back from LCROSS and other volatiles make this more realistic than previously thought; need to do this is a very cold place to manage the sublimation - this gives new possibilities, but also sets us back to the more research stage because we have to rethink how we might approach given the new potential resources. So we are probably at a TRL of 2.	**TRL 2**

TA7 HEDS Sustainability & Supportability

- **7.2 Sustainability & Supportability**
  - **7.2.1 Logistics Systems**
    - 7.2.1.1 Consumable Storage, Transfer, and Delivery
    - 7.2.1.2 Food Production & Preservation
    - 7.2.1.3 Reuse and Recycle
  - **7.2.2 Maintenance Systems**
    - 7.2.2.1 Intelligent/Smart systems
    - 7.2.2.2 Non-Destructive Evaluation & Analysis
    - 7.2.2.3 Robotic Systems for Maintenance
    - 7.2.2.4 Contamination Control & Cleanup
  - **7.2.3 Repair Systems**
    - 7.2.3.1 Advanced Materials and Processes
    - 7.2.3.2 Reconfigurability and Reusability


TA7 HEDS
72 Sustainability & Supportability
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
MMSEV
CTV
Test HEO
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO/NEA
Crewed NEO
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Human Mars ISRU
Return Prop Plant
Crewed Mars Orbit
Crewed Mars Surface
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
Human Deep Water Destination
LEO Artificial Gravity Research Facility
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
7.2.1 Logistics Systems
• Consumable Storage, Transfer, and Delivery
• Food Production & Preservation
• Reuse and Recycle
xPRM Lander Prop Scavenging
In-space Long-term Prop Storage &Transfer
In-Space Food Production & Preservation Research
ISS Trash Recycling Demo
Lunar Prop Storage & Transfer Demo
LEO Prop Servicing
In-Space Food Production & Preservation.
Trash Recycling
Mars Long-term Surface Prop Storage and Transfer Demo
Mars Food Production & Preservation Demo
Mars Long-term Surface Prop Storage and Transfer
Surface Food Production, Preservation
Propellant Scavenging & Descent Stage Re-usability
7.2.2 Maintenance Systems
• Intelligent/Smart Systems
• Non-Destructive Evaluation & Analysis
• Robotic Systems for Maintenance
• Contamination Control & Cleanup
Autonomous Maintenance System Demo on FTD Missions
Robotic Maintenance System for Satellite Service
ISS Contamination Control & Cleanup Research
Smart System Integrated Robotic & Human Spaceflight Missions
In-situ Repair Certification & Verification
In-Space Maintenance Robotic System
NDE Technology for Human Spaceflight Systems
Extreme Environment NDE Technologies
Contamination Control & Cleanup for NEO
Smart System Integrated Robotic & Human Spaceflight Missions
Autonomous Maintenance
NDE Certification & Verification for In-Situ Fab
Contamination Control & Cleanup for NEO
7.2.3 Repair Systems
• "Advanced " Materials & Processes
• Reconfigurability & Reusability
Advanced Materials Demo on FTD
ISS Advanced Materials Research
ISS Robotic Repair Demo
System & Components Commonality for Re-usability & Re-configurability
Extreme Environment Repair Technologies
Repair Process Technology for Manned Mission to NEO/NEA
System & Components Commonality for Re-usability and Re-configurability for Surface System
Autonomous Repair for Surface Mission

7.2 Sustainability & Supportability

7.2.1 Logistics Systems	Current State-of-the-Art Practice	Current TRL
Consumable Storage, Transfer, and Delivery	-discrete storage of the same consumable for each destination element -fluid and power connectors for transfer	**TRL 3**
Food Production, Processing & Preservation	-Foods Packaged for Space -Ground Controlled Environment Food Production--300 $W\ m^{-2}$ Electrical Power -Full scale Bioregenerative Life Support: 2 $kW\ m^{-2}$ -Short Durationμ-g Tests with Plants -Use of Existing Crop Varieties	**TRL 3-5**
Reuse and Recycle	-waste storage and brought back to Earth. -single use systems/components/consumables	**TRL 3-4**

7.2 Sustainability & Supportability

7.2.2 Maintenance Systems	Current State-of-the-Art Practice	Current TRL
Intelligent/Smart systems	- At the subsystem and system level, we remain very dependent on humans to make decisions; good applications are coming on line to help organize information but not ready to make decisions. -external intervention to isolate a problem -manual reconfiguration of analog signals circuits -manual inspection of electrical conductor -External diagnostics is used when the faults disable ISHM and Self test functions. -embedded sensors at the system level -fiber optics sensors	**TRL 3-5**
Non-Destructive Evaluation & Analysis	-Hand held internal ultrasonic leak location and pressure decline overall health -Visual scanning using robot arm or EVA cameras -Handheld portable Microwave Camera (MWC) able to provide 2D and 3D imaging of damaged areas of non-metals components. -Piezoelectric sensors for impact detection (e.g. leading edge Shuttle wing) Current technologies include Stanford Multi-Actuator Receiver Transduction (SMART) layer and Acoustic Emission . -Visual inspection of metallic/non-metallic parts and glass parts/surfaces	**TRL 2-5**
Robotic Systems for Maintenance	-robotic systems for repair are limited to tools	**TRL 3-5**
Contamination Control & Cleanup	-Chemicromic sensors (Drager tubes) -Direct sunlight space suit decontamination	**TRL 2-3**

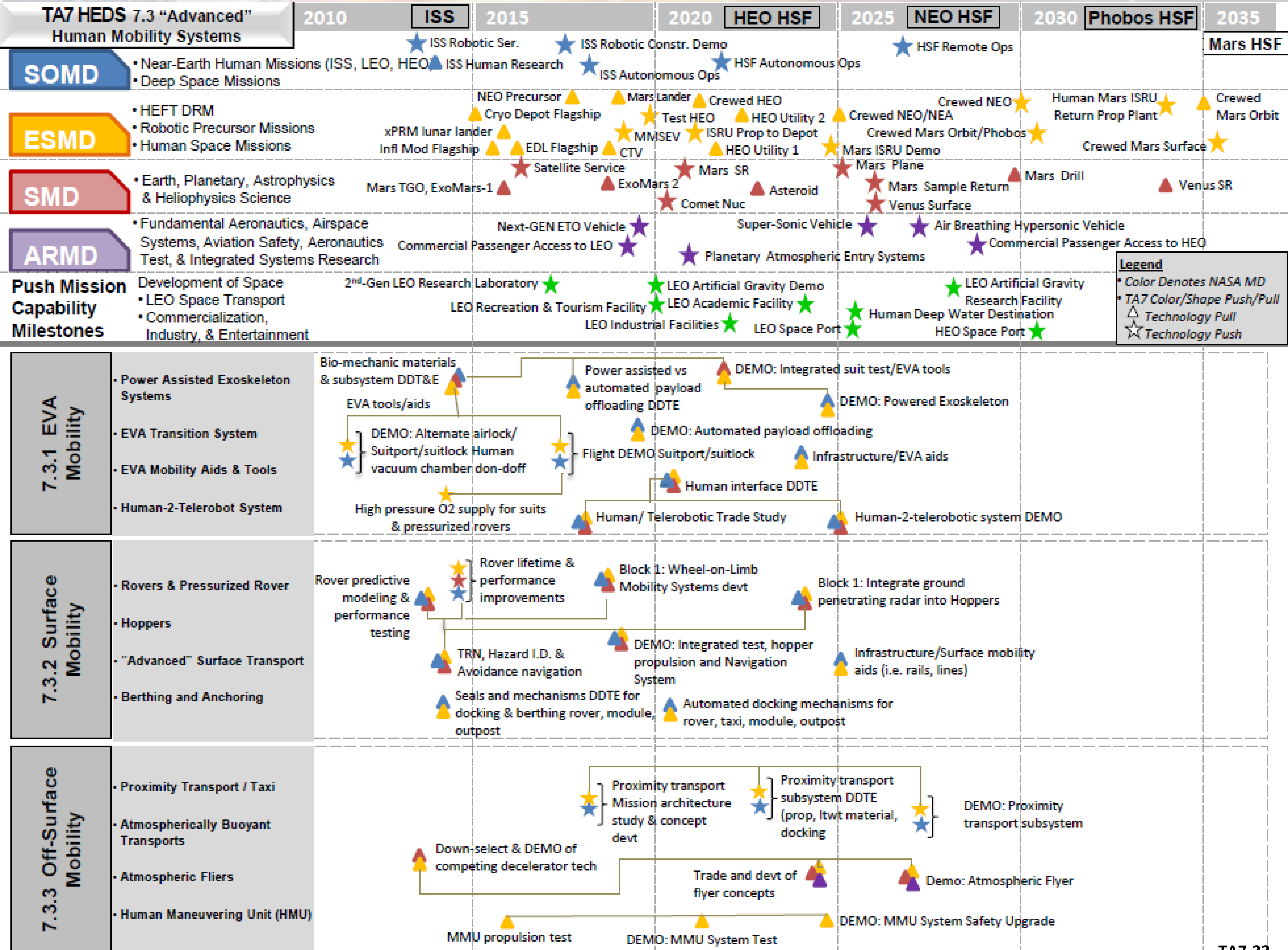
7.2 Sustainability & Supportability

7.2.3 Repair Systems	Current State-of-the-Art Practice	Current TRL
Advanced Materials and Processes	-Ground-based demonstrations of free-form fabrication using electron beam technology -Ground-based use of various welding technology pretty mature -Power and mass of ground-based equipment is not conducive to space applications -Ion process transport material at the molecular scale and are widely used in the manufacture of electronics and optical components. - current adhesives: epoxy, acrylic, urethanes, methacrylates in a film, paste, or pressure sensitive - current adhesives fail in shear and peel - Current repair method involves applying multiple wraps of repair tape over the damage or heat shrink - Repairs are not hermetic; i.e. offer limited environmental resistance - Self-healing technologies focus on composite materials - Self-healing systems typically utilize microencapsulated healing agents for repair - Self-healing process is typically slow Self-healing concrete - Self-healing composite materials - Self-repair process slow - ILC Dover investigating self-healing putty for habitats	**TRL 2-5**
Reconfigurability and Reusability	-Normally landing spacecraft are discarded or abandoned after a single use. A crewed lunar lander only leaves roughly 5% of its landing weight as useable payload. -Technology for using material from expended systems as feedstock for manufacturing new parts in space is in its infancy -Information systems to help identify components that are available to be repurposed when the need arises will be needed, and the technology to do so is available but not implemented -Many systems need to be powered down and taken off line to perform work -Notable examples of components that can be pulled and replaced from a system in operation - e.g. B-777 avionics modules -Most components are built to a spec for a particular purpose. -Few applications of mixed criticality use unless the non-critical application uses the higher rated component	**TRL 2-5**

TA7 HEDS Advanced Human Mobility Systems

7.3 “Advanced” Human Mobility Systems

- 7.3.1 EVA Mobility
  - 7.3.1.1 Power-Assisted Exoskeleton
  - 7.3.1.2 EVA Transition System
  - 7.3.1.3 EVA Mobility Aids & Tools
  - 7.3.1.4 Human-2-telerobot system
- 7.3.2 Surface Mobility
  - 7.3.2.1 Rovers & Pressurized Rover
  - 7.3.2.2 Hoppers
  - 7.3.2.3 Advanced Surface Transport
  - 7.3.2.4 Berthing & Anchoring
- 7.3.3 Off-Surface Mobility
  - 7.3.3.1 Proximity Transport / Taxi
  - 7.3.3.2 Atmospherically Buoyant Transports
  - 7.3.3.3 Atmospheric Fliers
  - 7.3.3.4 Human Maneuvering Units (HMU)


TA7 HEDS 7.3 "Advanced" Human Mobility Systems
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
Test HEO
MMSEV
CTV
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO/NEA
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Crewed NEO
Human Mars ISRU Return Prop Plant
Crewed Mars Surface
Crewed Mars Orbit
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
LEO Artificial Gravity Research Facility
Human Deep Water Destination
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
7.3.1 EVA Mobility
• Power Assisted Exoskeleton Systems
• EVA Transition System
• EVA Mobility Aids & Tools
• Human-2-Telerobot System
Bio-mechanic materials & subsystem DDT&E
EVA tools/aids
Power assisted vs automated payload offloading DDTE
DEMO: Integrated suit test/EVA tools
DEMO: Powered Exoskeleton
DEMO: Automated payload offloading
DEMO: Alternate airlock/ Suitport/suitlock Human vacuum chamber don-doff
Flight DEMO Suitport/suitlock
Infrastructure/EVA aids
Human interface DDTE
High pressure O2 supply for suits & pressurized rovers
Human/ Telerobotic Trade Study
Human-2-telerobotic system DEMO
7.3.2 Surface Mobility
• Rovers & Pressurized Rover
• Hoppers
• "Advanced" Surface Transport
• Berthing and Anchoring
Rover predictive modeling & performance testing
Rover lifetime & performance improvements
Block 1: Wheel-on-Limb Mobility Systems devt
Block 1: Integrate ground penetrating radar into Hoppers
TRN, Hazard I.D. & Avoidance navigation
DEMO: Integrated test, hopper propulsion and Navigation System
Infrastructure/Surface mobility aids (i.e. rails, lines)
Seals and mechanisms DDTE for docking & berthing rover, module, outpost
Automated docking mechanisms for rover, taxi, module, outpost
7.3.3 Off-Surface Mobility
• Proximity Transport / Taxi
• Atmospherically Buoyant Transports
• Atmospheric Fliers
• Human Maneuvering Unit (HMU)
Proximity transport Mission architecture study & concept devt
Proximity transport subsystem DDTE (prop, ltwt material, docking
DEMO: Proximity transport subsystem
Down-select & DEMO of competing decelerator tech
Trade and devt of flyer concepts
Demo: Atmospheric Flyer
MMU propulsion test
DEMO: MMU System Test
DEMO: MMU System Safety Upgrade

7.3 “Advanced” Human Mobility Systems

7.3.1 EVA Mobility	Current State-of-the-Art Practice	Current TRL
Power-Assisted Exoskeleton	teleoperated robotics	**TRL 1**
EVA Transition System	Airlock	**TRL 3-4**
EVA Mobility Aids & Tools	Handrails and SAFER	**TRL 2-3**
Human-2-Telerobot System	Virtual reality used for training	**TRL 3-5**

7.3 "Advanced" Human Mobility Systems

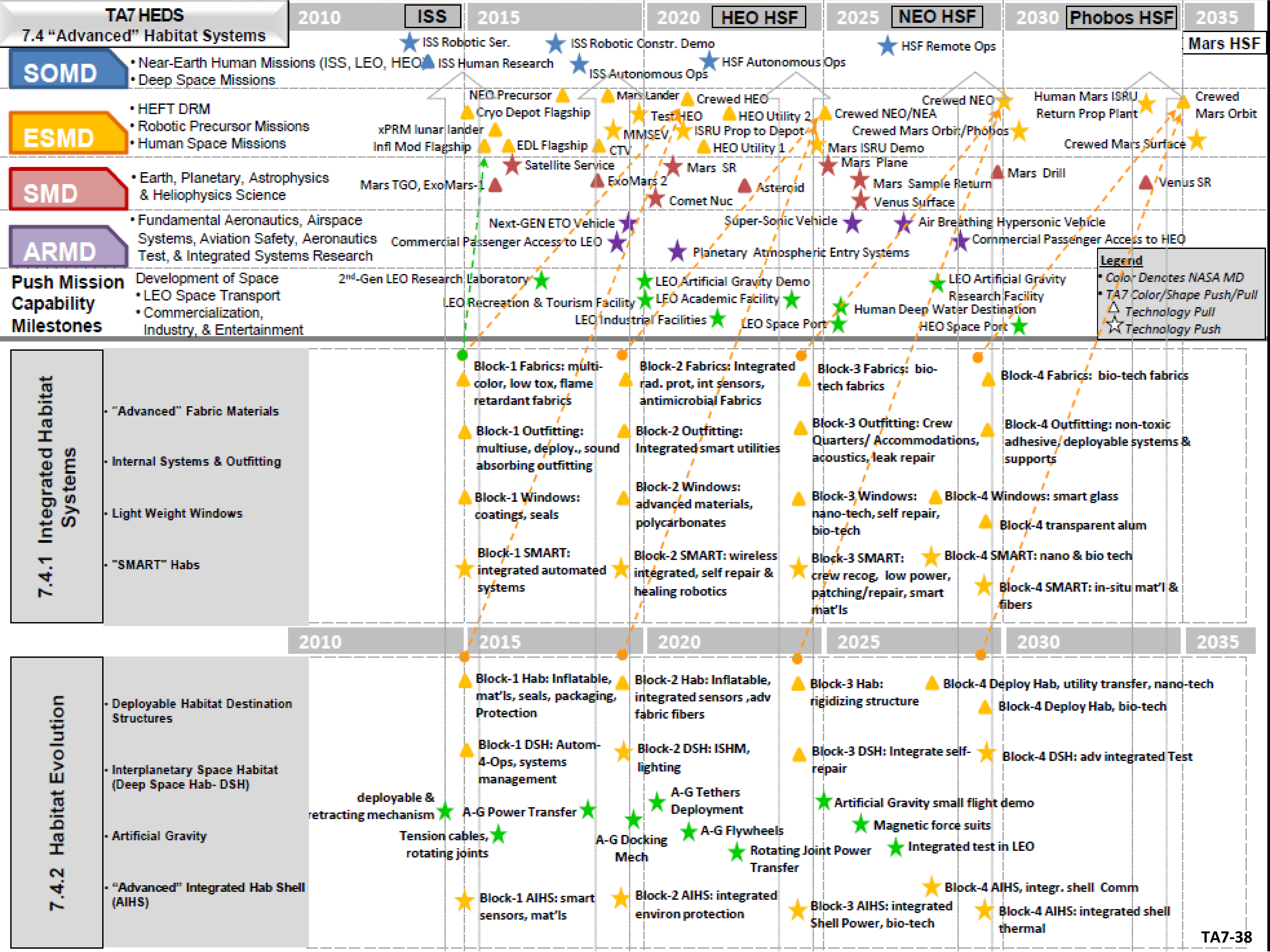
7.3.2 Surface Mobility	Current State-of-the-Art Practice	Current TRL
Rovers & Pressurized Rover	Apollo Lunar Rover; Analog testing of Athlete Rover;	**TRL 3-5**
Hoppers	- 1969 heritage concepts; - Google X-Prize concepts	**TRL 2-3**
Advanced Surface Transport	Shuttle EVA mobility tools (portable hand-holds, guide lines and rails No permanent destination infrastructure	**TRL 3 - 4**
Berthing and Anchoring	- on orbit ISS Docking and Berthing mechanisms demonstrated - surface analog testing and industrial applications demonstrated	**TRL 3 - 5**

7.3 "Advanced" Human Mobility Systems

7.3.3 Off-Surface Mobility	Current State-of-the-Art Practice	Current TRL
Proximity Transport / Taxi	- Earth to orbit taxi preliminary work initiated w/Commercial Crew - Google X Prize concepts	**TRL 2-3**
Atmospherically Buoyant Transports	- Inflatables and Decelerator technology demonstrated on science missions - Other concepts are being used in Extreme sports	**TRL 3 - 4**
Atmospheric Fliers	- Pressurized and unpressurized wing suits in earth atmosphere - Pressurized wing suits w/ small propulsive units tested in earth atmosphere but still developmental	**TRL 2-3**
Human Maneuvering Units (HMU)	- nitrogen canister jet propelled units - Simplified Aid For EVA Rescue (SAFER)	**TRL 4-5**

TA7 HEDS Advanced Habitat Systems

- **7.4 “Advanced” Habitat Systems**
  - **7.4.1 Integrated Habitat Systems**
    - 7.4.1.1 “Advanced” Fabric Materials
    - 7.4.1.2 Internal Systems & Outfitting
    - 7.4.1.3 Light Weight Windows
    - 7.4.1.4 "SMART" Habs
  - **7.4.2 Habitat Evolution**
    - 7.4.2.1 Deployable Habitat Destination Structures
    - 7.4.2.2 Interplanetary Space Habitat
    - 7.4.2.3 Artificial Gravity
    - 7.4.2.4 “Advanced” Integrated Hab Shells


TA7 HEDS
7.4 "Advanced" Habitat Systems
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
MMSEV
CTV
Test HEO
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO
Crewed NEO/NEA
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Human Mars ISRU Return Prop Plant
Crewed Mars Surface
Crewed Mars Orbit
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
Human Deep Water Destination
LEO Artificial Gravity Research Facility
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
7.4.1 Integrated Habitat Systems
• "Advanced" Fabric Materials
• Internal Systems & Outfitting
• Light Weight Windows
• "SMART" Habs
Block-1 Fabrics: multi-color, low tox, flame retardant fabrics
Block-1 Outfitting: multiuse, deploy., sound absorbing outfitting
Block-1 Windows: coatings, seals
Block-1 SMART: integrated automated systems
Block-2 Fabrics: Integrated rad. prot, int sensors, antimicrobial Fabrics
Block-2 Outfitting: Integrated smart utilities
Block-2 Windows: advanced materials, polycarbonates
Block-2 SMART: wireless integrated, self repair & healing robotics
Block-3 Fabrics: bio-tech fabrics
Block-3 Outfitting: Crew Quarters/ Accommodations, acoustics, leak repair
Block-3 Windows: nano-tech, self repair, bio-tech
Block-3 SMART: crew recog, low power, patching/repair, smart mat'ls
Block-4 Fabrics: bio-tech fabrics
Block-4 Outfitting: non-toxic adhesive, deployable systems & supports
Block-4 Windows: smart glass
Block-4 transparent alum
Block-4 SMART: nano & bio tech
Block-4 SMART: in-situ mat'l & fibers
2010
2015
2020
2025
2030
2035
7.4.2 Habitat Evolution
• Deployable Habitat Destination Structures
• Interplanetary Space Habitat (Deep Space Hab- DSH)
• Artificial Gravity
• "Advanced" Integrated Hab Shell (AIHS)
Block-1 Hab: Inflatable, mat'ls, seals, packaging, Protection
Block-1 DSH: Autom-4-Ops, systems management
deployable & retracting mechanism
A-G Power Transfer
Tension cables, rotating joints
Block-1 AIHS: smart sensors, mat'ls
Block-2 Hab: Inflatable, integrated sensors ,adv fabric fibers
Block-2 DSH: ISHM, lighting
A-G Tethers Deployment
A-G Docking Mech
A-G Flywheels
Rotating Joint Power Transfer
Block-2 AIHS: integrated environ protection
Block-3 Hab: rigidizing structure
Block-3 DSH: Integrate self-repair
Artificial Gravity small flight demo
Magnetic force suits
Integrated test in LEO
Block-3 AIHS: integrated Shell Power, bio-tech
Block-4 Deploy Hab, utility transfer, nano-tech
Block-4 Deploy Hab, bio-tech
Block-4 DSH: adv integrated Test
Block-4 AIHS, integr. shell Comm
Block-4 AIHS: integrated shell thermal

7.4 “Advanced” Habitat Systems

7.4.1 Integrated Habitat Systems	Current State-of-the-Art Practice	Current TRL
Advanced Fabric Materials	ISS Nomex	**TRL - 3**
Internal Systems & Outfitting	ISS Pre-Assembled or installed	**TRL - 4**
Light Weight Windows	ISS Multi-pane Windows STS Orbiter	**TRL - 3-4**
"SMART" Habs	ISS ground assisted ops heavy crew interaction and control	**TRL - 3-4**

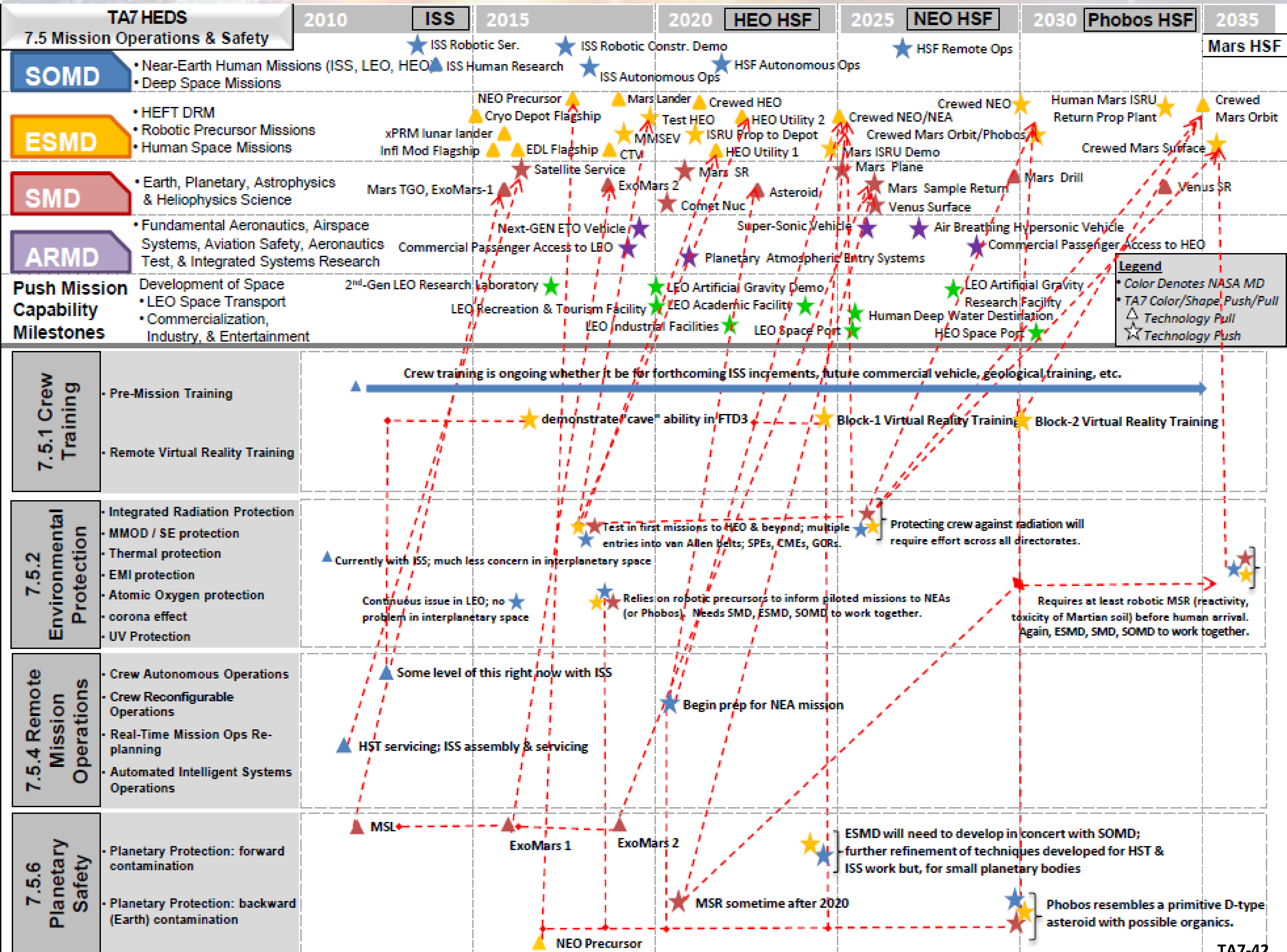
7.4 "Advanced" Habitat Systems

7.4.2 Habitat Evolution	Current State-of-the-Art Practice	Current TRL
Deployable Habitat Destination Structures	- Bigelow Aerospace - Antarctica Inflatable Hab	**TRL - 3-4**
Interplanetary Space Habitat	- ISS derived Modules and Spacecraft - Apollo	**TRL - 2**
Artificial Gravity	individual rotating apparatus	**TRL - 1-2**
Advanced Integrated Hab Shells	ISS MMOD Bumper Shield	**TRL - 3**

TA7 HEDS Mission Operations & Safety

7.5 Mission Operations & Safety

- 7.5.1 Crew training
  - 7.5.1.1 Pre-mission training
  - 7.5.1.2 Remote Virtual Reality Training
- 7.5.2 Environmental Protection
  - 7.5.2.1 Integrated Radiation protection
  - 7.5.2.2 MMOD & Secondary Ejecta protection
  - 7.5.2.3 Thermal protection
  - 7.5.2.4 EMI protection
  - 7.5.2.5 Atomic Oxygen protection
  - 7.5.2.6 corona effect
  - 7.5.2.7 UV Protection
- 7.5.3 Remote Mission Operations
  - 7.5.3.1 Crew Autonomous Operations
  - 7.5.3.2 Crew Reconfigurable Operations
  - 7.5.3.3 real-time mission ops re-planning
  - 7.5.3.4 Automated Intelligent systems Operations
- 7.5.4 Planetary Safety
  - 7.5.4.1 planetary protection: forward contamination
  - 7.5.4.2 planetary protection: backward contamination


TA7 HEDS
7.5 Mission Operations & Safety
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Human Research
ISS Robotic Constr. Demo
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
Test HEO
MMSEV
CTV
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO/NEA
Crewed Mars Orbit/Phobos
Mars ISRU Demo
Crewed NEO
Human Mars ISRU
Return Prop Plant
Crewed Mars Orbit
Crewed Mars Surface
SMD
• Earth, Planetary, Astrophysics
& Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
Human Deep Water Destination
LEO Artificial Gravity Research Facility
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
△ Technology Pull
☆ Technology Push
7.5.1 Crew Training
• Pre-Mission Training
• Remote Virtual Reality Training
Crew training is ongoing whether it be for forthcoming ISS increments, future commercial vehicle, geological training, etc.
demonstrate "cave" ability in FTD3
Block-1 Virtual Reality Training
Block-2 Virtual Reality Training
7.5.2 Environmental Protection
• Integrated Radiation Protection
• MMOD / SE protection
• Thermal protection
• EMI protection
• Atomic Oxygen protection
• corona effect
• UV Protection
Test in first missions to HEO & beyond; multiple entries into van Allen belts; SPEs, CMEs, GCRs.
Protecting crew against radiation will require effort across all directorates.
Currently with ISS; much less concern in interplanetary space
Continuous issue in LEO; no problem in interplanetary space
Relies on robotic precursors to inform piloted missions to NEAs (or Phobos). Needs SMD, ESMD, SOMD to work together.
Requires at least robotic MSR (reactivity, toxicity of Martian soil) before human arrival. Again, ESMD, SMD, SOMD to work together.
7.5.4 Remote Mission Operations
• Crew Autonomous Operations
• Crew Reconfigurable Operations
• Real-Time Mission Ops Re-planning
• Automated Intelligent Systems Operations
Some level of this right now with ISS
Begin prep for NEA mission
HST servicing; ISS assembly & servicing
7.5.6 Planetary Safety
• Planetary Protection: forward contamination
• Planetary Protection: backward (Earth) contamination
MSL
ExoMars 1
ExoMars 2
ESMD will need to develop in concert with SOMD; further refinement of techniques developed for HST & ISS work but, for small planetary bodies
MSR sometime after 2020
Phobos resembles a primitive D-type asteroid with possible organics.
NEO Precursor

7.5 Mission Operations & Safety

7.5.1 Crew training	Current State-of-the-Art Practice	Current TRL
Pre-mission training	- Nominal and off-nominal training conducted for short and long duration missions - Training content includes dynamic flight, vehicle systems management, emergency response, on-board maintenance and repair, EVA tasks, robotics operations and daily housekeeping tasks. - Training environments and systems including self-study, classroom instruction, computer based training, part-task trainers, high-fidelity simulations, vehicle mockups, virtual reality, neutral buoyancy training and on-board training exercises.	**TRL-9 for shuttle and ISS training systems.** **TRL-6 for exploration systems.**
Remote Virtual Reality Training	- Limited on-board CBT capability. - On-board emergency response drills conducted on a regular basis. - Real-time ground led training for unplanned for contingencies.	**TRL-3**

7.5 Mission Operations & Safety

7.5.2 Environmental Protection	Current State-of-the-Art Practice	Current TRL
Integrated Radiation protection (SPE, GCR, CME)	- to/from ISS (also depends upon individual crewmember's lifetime dose) - none for interplanetary space voyages	**TRL-3/4 for interplanetary**
MMOD & Secondary Ejecta Protection	- Used on ISS - none for deep space mission (but, designing for LEO will satisfy for other deep space destinations)	**TRL-4**
Thermal protection	- Used on ISS	**TRL-4**
EMI protection	- Used on ISS	**TRL-3**
Atomic Oxygen protection	- Used on ISS	**TRL-4**
corona effect	- Used on Satellites	**TRL-4**
UV Protection	- Used on ISS	**TRL-4**

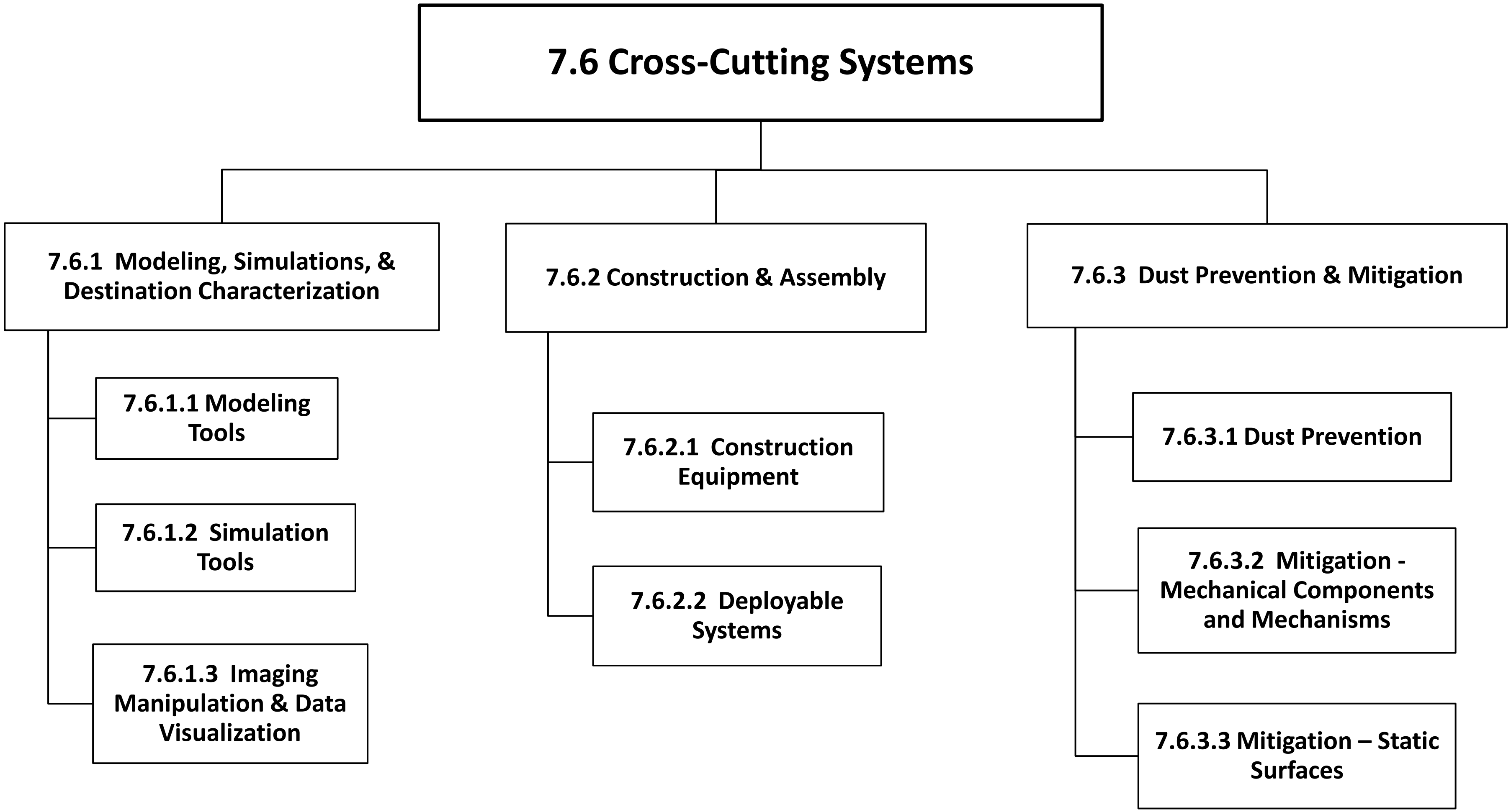
7.5 Mission Operations & Safety

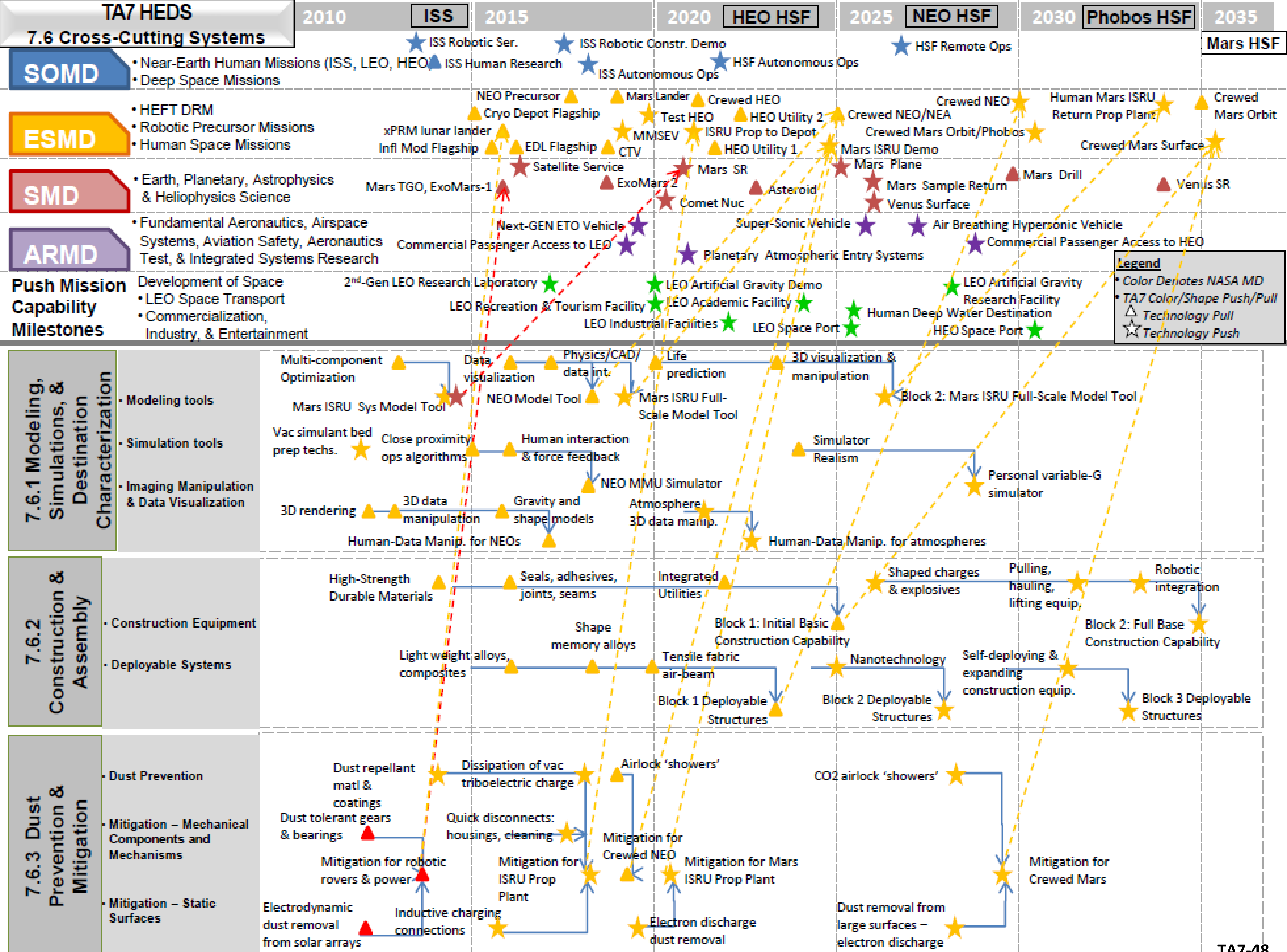
7.5.3 Remote Mission Operations	Current State-of-the-Art Practice	Current TRL
Crew Autonomous Operations	- Emergency C&W procedures	**TRL-6**
Crew Reconfigurable Operations	- currently done on ISS (with MCC guidance & prior training)	**TRL-6**
Real-time mission ops re-planning	-constantly done on ISS (primary focus on MCC personnel)	**TRL-6**
Automated Intelligent systems Operations (software)	- Aircraft Flight Systems - ISS - Hab Demo Unit Prototype	**Spacecraft TRL-3/4**

7.5 Mission Operations & Safety

7.5.4 Planetary Safety	Current State-of-the-Art Practice	Current TRL
planetary protection - forward contamination	- on all robotic surface missions to Mars	**TRL-6**
planetary protection - backward contamination (back to Earth)	- performed on Stardust return sample	**TRL-6**
Planetary defense	- most ground-based - some with NEOWISE (data TBR) Need IR survey telescope in Venus-like orbit to complete survey [and find human accessible targets as well as inform planetary defense] - limited - Deep Impact impactor probe	**TRL-6** **TRL-1 or -2**

TA7 HEDS Cross-Cutting Systems




TA7 HEDS
7.6 Cross-Cutting Systems
2010
ISS
2015
2020
HEO HSF
2025
NEO HSF
2030
Phobos HSF
2035
Mars HSF
SOMD
• Near-Earth Human Missions (ISS, LEO, HEO)
• Deep Space Missions
ISS Robotic Ser.
ISS Robotic Constr. Demo
ISS Human Research
ISS Autonomous Ops
HSF Autonomous Ops
HSF Remote Ops
ESMD
• HEFT DRM
• Robotic Precursor Missions
• Human Space Missions
NEO Precursor
Cryo Depot Flagship
xPRM lunar lander
Infl Mod Flagship
EDL Flagship
Mars Lander
Test HEO
MMSEV
CTV
Crewed HEO
HEO Utility 2
ISRU Prop to Depot
HEO Utility 1
Crewed NEO/NEA
Mars ISRU Demo
Crewed NEO
Crewed Mars Orbit/Phobos
Human Mars ISRU Return Prop Plant
Crewed Mars Orbit
Crewed Mars Surface
SMD
• Earth, Planetary, Astrophysics & Heliophysics Science
Mars TGO, ExoMars-1
Satellite Service
ExoMars 2
Mars SR
Comet Nuc
Asteroid
Mars Plane
Mars Sample Return
Venus Surface
Mars Drill
Venus SR
ARMD
• Fundamental Aeronautics, Airspace Systems, Aviation Safety, Aeronautics Test, & Integrated Systems Research
Next-GEN ETO Vehicle
Commercial Passenger Access to LEO
Planetary Atmospheric Entry Systems
Super-Sonic Vehicle
Air Breathing Hypersonic Vehicle
Commercial Passenger Access to HEO
Push Mission Capability Milestones
Development of Space
• LEO Space Transport
• Commercialization, Industry, & Entertainment
2nd-Gen LEO Research Laboratory
LEO Recreation & Tourism Facility
LEO Industrial Facilities
LEO Artificial Gravity Demo
LEO Academic Facility
LEO Space Port
Human Deep Water Destination
LEO Artificial Gravity Research Facility
HEO Space Port
Legend
• Color Denotes NASA MD
• TA7 Color/Shape Push/Pull
Technology Pull
Technology Push
7.6.1 Modeling, Simulations, & Destination Characterization
• Modeling tools
• Simulation tools
• Imaging Manipulation & Data Visualization
Multi-component Optimization
Mars ISRU Sys Model Tool
Data visualization
Physics/CAD/ data int.
NEO Model Tool
Life prediction
Mars ISRU Full-Scale Model Tool
3D visualization & manipulation
Block 2: Mars ISRU Full-Scale Model Tool
Vac simulant bed prep techs.
Close proximity ops algorithms
Human interaction & force feedback
NEO MMU Simulator
Simulator Realism
Personal variable-G simulator
3D rendering
3D data manipulation
Gravity and shape models
Human-Data Manip. for NEOs
Atmosphere 3D data manip.
Human-Data Manip. for atmospheres
7.6.2 Construction & Assembly
• Construction Equipment
• Deployable Systems
High-Strength Durable Materials
Seals, adhesives, joints, seams
Integrated Utilities
Block 1: Initial Basic Construction Capability
Shaped charges & explosives
Pulling, hauling, lifting equip.
Robotic integration
Block 2: Full Base Construction Capability
Light weight alloys, composites
Shape memory alloys
Tensile fabric air-beam
Block 1 Deployable Structures
Nanotechnology
Block 2 Deployable Structures
Self-deploying & expanding construction equip.
Block 3 Deployable Structures
7.6.3 Dust Prevention & Mitigation
• Dust Prevention
• Mitigation – Mechanical Components and Mechanisms
• Mitigation – Static Surfaces
Dust repellant matl & coatings
Dissipation of vac triboelectric charge
Airlock 'showers'
CO2 airlock 'showers'
Dust tolerant gears & bearings
Quick disconnects: housings, cleaning
Mitigation for Crewed NEO
Mitigation for robotic rovers & power
Mitigation for ISRU Prop Plant
Mitigation for Mars ISRU Prop Plant
Mitigation for Crewed Mars
Electrodynamic dust removal from solar arrays
Inductive charging connections
Electron discharge dust removal
Dust removal from large surfaces – electron discharge

7.6 Cross-Cutting Systems

7.6.1 Modeling, Simulations, & Destination Characterization	Current State-of-the-Art Practice	Current TRL
Modeling tools	- empirical models - independent platforms - standalone component and system models - physics-based models for O2 extraction from regolith using hydrogen reduction have been validated to predict production efficiency within ±10 - 15% - most other ISRU physics models have insufficient hardware data for validation - parametric mass models of systems at low development level - parametric 2-D thermal models operating separately from parametric performance models -much of soil mechanics at continuum level is low TRL 2 - 3	**Modeling Tools, etc: TRL 2 - 4**
Simulation tools	- Shuttle Simulator - Partial Gravity Simulator (POGO) - Underwater Gravity Simulator - JSC-1A 'chemical' lunar simulant; LHT 'geotechnical' lunar simulant - No large 'dirty' thermal vacuum chambers exist in NASA	**TRL 3-4** **Simulants:** **NEO, Mars: TRL 2** **lunar: TRL 5**
Imaging Manipulation and Data Visualization	- LIDAR for digital elevation modeling (gives shape model) - virtual reality tools for Hubble, ISS (ground-based) - spend 6 - 10 months in vicinity of object to map gravity field before deploying instruments -Haptic feedback - use the gloves to manipulate 3-D images; using it for interatomic forces in molecules as a research tool	**TRL 3 - 4**

7.6 Cross-Cutting Systems

7.6.2 Construction & Assembly	Current State-of-the-Art Practice	Current TRL
Construction Equipment	- ISS Assembly - arm, etc.; have good technology in control, feedback, etc. - Soviets dock Progress autonomously - no demo of in-space welding for a joining technique or related cutting techniques - lunar surface manipulation system (in development under HRS) can do digging, manipulation, assembly (ATHLETE, LSMS) -have Dexter on station now as a two-arm end effectors that could maybe do assembly in general: EVA Assembly very high; robotic lower but terrestrial capability; other joining techniques like welding, etc is even lower	**TRL 2 - 5**
Deployable Systems	- in-space erectable truss assembly using EVA (experiment in '85 or '86 called ACCESS, and Shuttle exp called ASEM) - Sundancer (Bigelow) working inflatable habitats, has two flying now at 1/6th scale. Claim is that has everything needed to do 1/3rd scale then full scale in next 4 - 5 years, but not everyone agrees. Doesn't have all the life support that is needed to call it a Hab - almost every satellite has a deployable antenna (some as long as 20 m) or mast; applications are all comm, nav, etc. -J Webb is deployable telescope that would bring demo up to 6.8 m size	**TRL 4**

7.6 Cross-Cutting Systems

7.6.3 Dust Prevention & Mitigation	Current State-of-the-Art Practice	Current TRL
Prevention	- Airlock as 'buffer' area for Hab - Suitport/suitlock (still being developed) - use of seals	**TRL 3 - 4**
Mitigation - Mechanical Components and Mechanisms	- mitigation by design - shaft seals - high TRL - used lots of grease on MER, dust floats up to top to keep out of gears, etc. - terrestrial: frequent change out of soft goods (seals, o-rings)	**TRL 2 - 4**
Mitigation -Static Surfaces	-brushes (radiator applications) - blowing gas (naturally happened on Mars MER rovers) - electrodynamic dust shield (TRL 4)	**TRL 3 - 4**

TA07 HEDS Summary

- Preliminary Definition of TA7 Human Exploration Destination Systems
  - Melting-Pot of destination technologies
  - Applied Technologies leading to Capabilities
- Identified Push Missions for maturation of game-changing technologies
- Identified Top Technical Challenges
- Forward Work
  - Validation of Technology readiness level
  - path to TRL 6
  - key performance parameters
  - cost analysis

Back-up Slides

Dependency & Collaboration Matrix

7.0 Human Exploration Destination Systems	TA1: Launch Propulsion Systems	TA2: In-Space Propulsion Systems	TA3: Space Power and Energy Storage Systems	TA4: Robotics, Tele-Robotics, and Autonomous Systems	TA5: Communication and Navigation Systems	TA6: Human Health, Life Support and Habitation Systems	TA7: Human Exploration Destination Systems	TA8: Scientific Instruments, Observatories, and Sensor Systems	TA9: Entry, Descent, and Landing Systems	TA10: Nanotechnology	TA11: Modeling, Simulation, Information Technology and Processing	TA12: Materials, Structural & Mechanical Systems, and Manufacturing	TA13: Ground and Launch Systems Processing	TA14: Thermal Management Systems
7.1 In-Situ Resource Utilization														
7.1.1 Destination Reconnaissance, Prospecting, & Mapping				Yellow	Red	Red		Red	Green		Yellow			Green
7.1.2 Resource Acquisition				Yellow	Green						Yellow	Yellow		Red
7.1.3 Consumables Production	Green	Green	Green		Yellow					Green	Yellow	Yellow		Red
7.1.4 Manufacturing & Infrastructure Emplacement		Green	Yellow	Green	Yellow	Green				Green	Yellow	Yellow		Red
7.2 Sustainability & Supportability														
7.2.1 Logistics Systems		Yellow	Yellow			Green			Green				Green	Red
7.2.2 Maintenance Systems		Red	Red	Yellow	Red	Yellow		Yellow	Red			Red	Green	Red
7.2.3 Repair Systems		Yellow	Yellow	Yellow	Yellow	Yellow		Yellow	Yellow	Green		Yellow	Green	Yellow
7.3 Advanced Human Mobility Systems														
7.3.1 EVA Mobility				Red	Red	Red		Red				Red		Red
7.3.2 Surface Mobility		Red	Red	Yellow	Red	Red		Red	Yellow			Red		Red
7.3.3 Off-Surface Mobility		Red	Red	Yellow	Red	Red		Red	Yellow		Yellow	Red		Red
7.4 Advanced Habitat Systems														
7.4.1 Integrated Habitat Systems			Yellow	Yellow	Yellow	Yellow		Green		Yellow	Yellow	Yellow	Green	Green
7.4.2 Habitat Evolution			Yellow	Yellow	Green	Green		Green		Yellow	Green	Red	Green	Green
7.5 Mission Operations & Safety														
7.5.1 Crew training	Red	Red	Red	Yellow	Red	Red		Yellow	Red	Green	Yellow	Yellow	Yellow	Yellow
7.5.2 Environmental Protection	Green	Yellow	Green	Yellow		Yellow		Yellow	Yellow	Green	Red	Red		Red
7.5.3 Remote Mission Operations	Yellow	Yellow	Yellow	Yellow	Red	Yellow		Yellow	Yellow		Yellow			Yellow
7.5.4 Planetary Safety	Yellow	Yellow	Yellow	Yellow	Yellow	Red		Yellow	Red		Red	Yellow	Yellow	Red
7.6 Cross-Cutting Systems														
7.6.1 Modeling, Simulations, & Destination Characterization								Yellow			Red			
7.6.2 Construction & Assembly				Green								Green		
7.6.3 Dust Prevention & Mitigation		Green	Green	Green	Green					Green				Green

Red: Dependency
Yellow: Dependency and Collaboration
Green: Collaboration

Dependency & Collaboration

selected examples

7.1 In-Situ Resource Utilization

- Dependent on TA4 for high strength robot arms for end effectors for resource acquisition and regolith manipulation. Dexterous manipulation and robot hands for size sorting, beneficiation, up-close analysis of materials. TA12: Environment evaluation for materials used or mined in situ.
- Collaborate with TA9 on atmosphere and surface characterization tools. TA12: Manufacturing processes in situ using in situ resources/materials

7.2 Sustainability & Supportability

- Dependent on TA3 for high energy density systems for consumable depot (regenerative fuel cells and electrolysis systems). TA12: Repair technology related to welding, rapid prototyping, self-healing components
- Collaborate with TA6 on in-space and destination food production, waste management. TA4 Precision manipulators, microbots, high level of dexterity manipulators and systems

7.3 "Advanced" Human Mobility Systems

- Dependent on TA2 for thrusters for near-surface mobility (single MMU or small pressurized craft) at NEOs, moons
- Collaborate with TA4 on surface rovers, autonomous control, mobility mechanisms

Dependency & Collaboration

selected examples

7.4 "Advanced" Habitat Systems

- Dependent on TA3: integrated power management & distribution for low power wireless distribution; Self-Healing wiring. TA10 and TA12 for fibers, micro-sensors, light-weight, high-strength translucent materials, self-repairing, self-healing materials, coatings, etc.
- Collaborate with TA3 and TA5 on connectorless utilities integration (power, ECLSS, data, comm), integrated sensors, micro-systems integration. TA8 bio-technology coating for toxicity detection; bio-sensing; bio-technology coating for illumination

7.5 Mission Operations & Safety

- Dependent on TA1 and TA2 for definition of vehicle reactions for crew training simulators. TA4 autonomous operations
- Collaborate with TA8 on sensors, instruments, and observatories to identify environmental hazards requiring mitigation. TA12 materials

7.6 Cross-Cutting Systems

- Dependent on TA11 for multi-core computing, adaptive systems, simulation-based systems engineering, frameworks.
- Collaborate with TA3 on integration of dust mitigation technologies into solar panels and battery charging connectors/inductors. TA2 coordination of fittings for propellant transfer lines. TA10 on coatings for both nanotechnology and dust mitigation purposes

HEDS Mapped to National Needs

7.0 Human Exploration Destination Systems	Science & Technology	Security (Homeland Sec, DoD)	Energy	Health	Transportation (planes, trains, and automobiles)	Environment	Infrastructure (Utilities, Roads, Bridges, Harbors)	Agriculture	Education	Architecture, Engineering & Building Industry	Tourism, Entertainment, Leisure Industry	Disaster Relief & Support
7.1 In-Situ Resource Utilization												
7.1.1 Destination Reconnaissance, Prospecting, & Mapping	Major Impact	Applicability	Applicability	Applicability	Applicability	Applicability	Applicability	Applicability	Applicability	Applicability		Applicability
7.1.2 Resource Acquisition	Major Impact	Applicability	Applicability		Applicability	Applicability	Major Impact	Applicability	Applicability	Applicability		
7.1.3 Consumables Production	Major Impact	Applicability	Major Impact	Applicability	Applicability	Major Impact	Applicability	Applicability	Applicability	Applicability		Applicability
7.1.4 Manufacturing & Infrastructure Emplacement	Major Impact	Major Impact	Major Impact	Major Impact	Major Impact	Applicability	Major Impact	Applicability	Applicability	Applicability		Major Impact
7.2 Sustainability & Supportability												
7.2.1 Logistics Systems		Major Impact	Major Impact	Applicability		Applicability	Applicability	Major Impact				
7.2.2 Maintenance Systems	Applicability	Applicability			Applicability		Major Impact			Major Impact		Major Impact
7.2.3 Repair Systems	Major Impact	Major Impact			Major Impact		Major Impact			Major Impact		
7.3 Advanced Human Mobility Systems												
7.3.1 EVA Mobility	Applicability				Applicability							
7.3.2 Surface Mobility		Applicability	Applicability		Applicability		Applicability			Applicability		
7.3.3 Off-Surface Mobility		Applicability			Applicability						Major Impact	
7.4 Advanced Habitat Systems												
7.4.1 Integrated Habitat Systems	Major Impact		Major Impact	Applicability	Major Impact		Applicability		Major Impact	Major Impact	Applicability	Applicability
7.4.2 Habitat Evolution	Applicability				Major Impact				Major Impact	Major Impact	Major Impact	Major Impact
7.5 Mission Operations & Safety												
7.5.1 Crew training	Applicability	Major Impact	Applicability	Major Impact	Applicability	Applicability	Applicability		Major Impact	Applicability	Applicability	Applicability
7.5.2 Environmental Protection	Major Impact	Major Impact	Major Impact	Major Impact	Applicability	Major Impact	Applicability		Applicability	Applicability		Major Impact
7.5.3 Remote Mission Operations	Applicability	Major Impact	Major Impact	Major Impact	Major Impact	Applicability	Applicability	Applicability	Major Impact	Major Impact	Applicability	Major Impact
7.5.4 Planetary Safety	Major Impact	Applicability		Major Impact	Applicability	Major Impact		Major Impact	Major Impact		Major Impact	Major Impact
7.6 Cross-Cutting Systems												
7.6.1 Modeling, Simulations, & Destination Characterization	Applicability	Major Impact		Applicability					Applicability	Major Impact	Major Impact	Applicability
7.6.2 Construction & Assembly							Applicability				Applicability	Major Impact
7.6.3 Dust Prevention & Mitigation		Applicability	Major Impact									Applicability

Applicability

Major Impact

Benefits to National Needs

selected examples: major impacts

➢ 7.1 In-Situ Resource Utilization

- **Environment**: Mars atmosphere processing technologies for Earth atmosphere and water cleanup; recycling, re-purposing technologies for solid and liquid environmental wastes. **Energy**: Development of new types of "green" fuels from non-traditional sources. **Security**: Development of technologies that can be deployed real-time in the field to produce products (infrastructure, parts, tools, structures, etc.) quickly as needed

➢ 7.2 Sustainability & Supportability

- **Agriculture**: food growth technology for healthier crops. **Transportation**: Advanced Materials for transportation applications (self-healing plane skins and wire insulation, minimum intrusive repair tech). **Infrastructure**: Advanced Materials for infrastructure applications (self-healing asphalt, concrete, anti-corrosion materials or coatings)

➢ 7.3 “Advanced” Human Mobility Systems

- **Transportation**: terrain relative navigation, high-efficiency electric drives

Benefits to National Needs

selected examples: major impacts

7.4 "Advanced" Habitat Systems

- **Architecture and Building**: smart fabrics (self-cleaning, self-healing, color changing), internal systems & outfitting (connector-less utilities, sensors), windows (self-repairing, transparent aluminum, induced variable translucency. **Energy**: Advances in windows (multi-purpose coatings, nano-technology, light-weight high-strength translucent materials, self-repairing, self-healing, bio-technology coatings, transparent aluminum, induced variable translucency ('smart' glass)). **Disaster Relief:** Advances in deployable destination structures (long life durable textile materials, air-inflated, air-supported, self-rigidized air beams., high strength fabric fibers, self-rigidizing structures, self-healing, nano-tech integration, bio-technology integration)

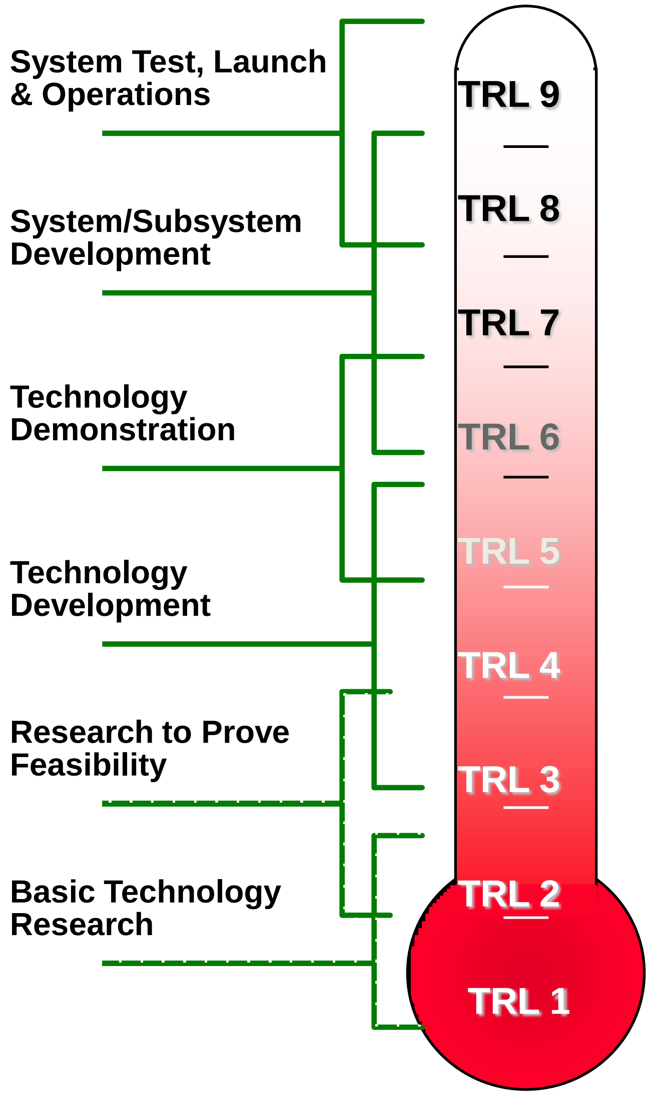
7.5 Mission Operations & Safety

- **Health and Education**: technologies for telemedicine and virtual reality training for remote crews applicable to remote locations on Earth. **Energy:** autonomous operations of mini-bots and nano-bots for integrated system health management and safe operation of the Nation's energy needs. **Infrastructure**: New environmental protection materials, alloys, engineering techniques to enable bridges, harbors, etc. to last longer and withstand the extremes of environment (water, wind, sea).

7.6 Cross-Cutting Systems

- **Security**: identification & characterization of Earth impacting asteroids. **Disaster Relief**: Rapid deployable shelters. **Entertainment**: flight simulators for entertainment and 3D data visualization and manipulation technologies for 'video' games.

NASA Technology Readiness Levels (TRL)



Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported