Joint Discussion: National Research Council "Pathways to Exploration" Report and NASA Human Exploration Strategy

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Setting the Stage: Inputs to This Presentation

- Follows a joint presentation to ASEB/SSB in April 2015
- Top-level findings of the NRC Human Spaceflight Committee as described in the "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration" (June, 2014)
- Current positioning of the report (a year after publication) v. NASA planning informed by consultations with other members of the committee, discussions with the NRC, and discussions with NASA officials.
- Characterization of the intentions for of the report come from discussions with Congressional staff who wrote the original authorization language directing the study, and with the NRC
- Personal observations (at the request of the NRC)

The "Pathways Report": Background

- The study was requested by Congress in the 2010 NASA Authorization Act after the political upheaval stemming from cancellation of the Constellation program
  - Multi-part, multi-disciplinary Statement of Task negotiated between NASA and NRC over a year (2011-2012)
  - Committee began work in Fall 2012, review-revision cycle began in Spring 2014, final publication in June of 2014.
- Representatives of past and current NASA and foreign programs, as well as experts from academia and industry, all provided briefings to the Technical Panel and the committee
- Key stakeholders were surveyed, a call to the public to submit white papers addressing the role of human spaceflight and its future was made, and the study was opened to public input via Twitter – all coordinated by the committee and the Public and Stakeholder Opinions Panel

Framing the Report: Multiple Goals

- The NRC "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration" report was requested in order to provide policy guidance *to Congress* regarding future direction and investments in the U.S. civil space program
  - Though asked to take policy and previous reports into account, the committee's deliberations and recommendations were not bound by existing policy – with the exception of using SLS and Orion in scenarios
  - Not intended to dictate program structure, architectures, or mission planning to NASA
- Per Congressional staff (authorizers): The underlying goal was to assemble a diverse group of experts, some of whom supported HSF and some who did not, to investigate, evaluate and recommend to the nation a *sustainable* path forward for HSF
  - Hope was that the committee could answer fundamental questions– why pursue human spaceflight into the future? Should we continue?*
  - If this group of people could not come to consensus that HSF was worth continued investment – "we have a much bigger problem than near-term authorization". ***This was the whole genesis for the study.***

NASA is Implementing the 2010 Auth Act and NSP

- **2010 NASA Authorization Act**
  - Use of ISS to enable expanded commercial presence in LEO and to enable long-duration human missions in space “with decreasing reliance on Earth”
  - Enable commercial cargo and crew transportation to ISS
  - Development of SLS and Orion
  - Long-term goal of international exploration of Mars, starting with missions using SLS/Orion to cis-lunar space
- **2010 US National Space Policy**
  - Set far-reaching exploration milestones. By 2025, begin crewed missions beyond the moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth

Committee Membership

COMMITTEE ON HUMAN SPACEFLIGHT

JONATHAN LUNINE, Cornell University, *Co-Chair*
MITCHELL E. DANIELS, JR., Purdue University, *Co-Chair*
BERNARD F. BURKE, Massachusetts Institute of Technology (emeritus professor)
MARY LYNNE DITTMAR, Dittmar Associates Inc.
PASCALE EHRENFREUND, George Washington University
JAMES S. JACKSON, University of Michigan
FRANK G. KLOTZ,[1] Council on Foreign Relations
FRANKLIN D. MARTIN, Martin Consulting, Inc.
DAVID C. MOWERY, University of California, Berkeley (emeritus professor)
BRYAN D. O'CONNOR, Independent Aerospace Consultant
STANLEY PRESSER, University of Maryland
HELEN R. QUINN, SLAC National Accelerator Laboratory (emeritus professor)
ASIF A. SIDDIQI, Fordham University
JOHN C. SOMMERER, Johns Hopkins University (retired)
ROGER TOURANGEAU, Westat
ARIEL WALDMAN, Spacehack.org
CLIFF ZUKIN, Rutgers University

Public & Stakeholder Opinions Panel

ROGER TOURANGEAU, Westat, *Chair*
MOLLY ANDOLINA, DePaul University
JENNIFER L. HOCHSCHILD, Harvard University
JAMES S. JACKSON, University of Michigan
ROGER D. LAUNIUS, Smithsonian Institution
JON D. MILLER, University of Michigan
STANLEY PRESSER, University of Maryland
CLIFF ZUKIN, Rutgers University

Technical Panel

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DOUGLAS S. STETSON, Space Science and Exploration Consulting Group, *Vice Chair*
ARNOLD D. ALDRICH, Aerospace Consultant
DOUGLAS M. ALLEN, Independent Consultant
RAYMOND E. ARVIDSON, Washington University in St. Louis
RICHARD C. ATKINSON, University of California, San Diego (professor emeritus)
ROBERT D. BRAUN, Georgia Institute of Technology
ELIZABETH R. CANTWELL, Lawrence Livermore National Laboratory
DAVID E. CROW, University of Connecticut (professor emeritus)
RAVI B. DEO, EMBR
ROBERT S. DICKMAN, RD Space LLC
DAVA J. NEWMAN, Massachusetts Institute of Technology
JOHN ROGACKI, Florida Institute for Human and Machine Cognition (Ocala)
GUILLERMO TROTTI, Trotti and Associates Inc.
LINDA A. WILLIAMS, Wyle Aerospace Group

The Statement of Task I:

Consider the goals for the human spaceflight program as set forth in (a) the National Aeronautics and Space Act of 1958, (b) the National Aeronautics and Space Administration Authorization Acts of 2005, 2008, ad 2010, and (c) the National Space Policy of the United States (2010), and any existing statement of space policy issued by the president of the United States.

Solicit broadly-based, but directed, public and stakeholder input to understand better the motivations, goals, and possible evolution of human spaceflight – that is, the foundations of a rationale for a compelling and sustainable U.S. human spaceflight program – and to characterize its value to the public and other stakeholders.

Describe the expected value and value proposition of NASA's human spaceflight activities in the context of national goals – including the needs of government, industry, the economy, and the public good – and in the context of the priorities and programs of current and potential international partners in the spaceflight program.

Identify a set of high-priority enduring questions that describe the rationale for and value of human exploration in a national and international context. The questions should motivate a sustainable direction for the long-term exploration of space by humans. The enduring questions may include scientific, engineering, economic, cultural, and social science questions to be addressed by human space exploration and questions on improving the overall human condition.

The Statement of Task II:

Consider prior studies examining human space exploration, and NASA's work with international partners, to understand possible exploration pathways (including key technical pursuits and destinations) and the appropriate balance between the "technology push" and "requirements pull". Consideration should include the analysis completed by NASA's Human Exploration Framework Team, NASA's Human Spaceflight Architecture Team, and the Review of U.S. Human Spaceflight Plans (Augustine Commission), previous NRC reports, and relevant reports identified by the committee.

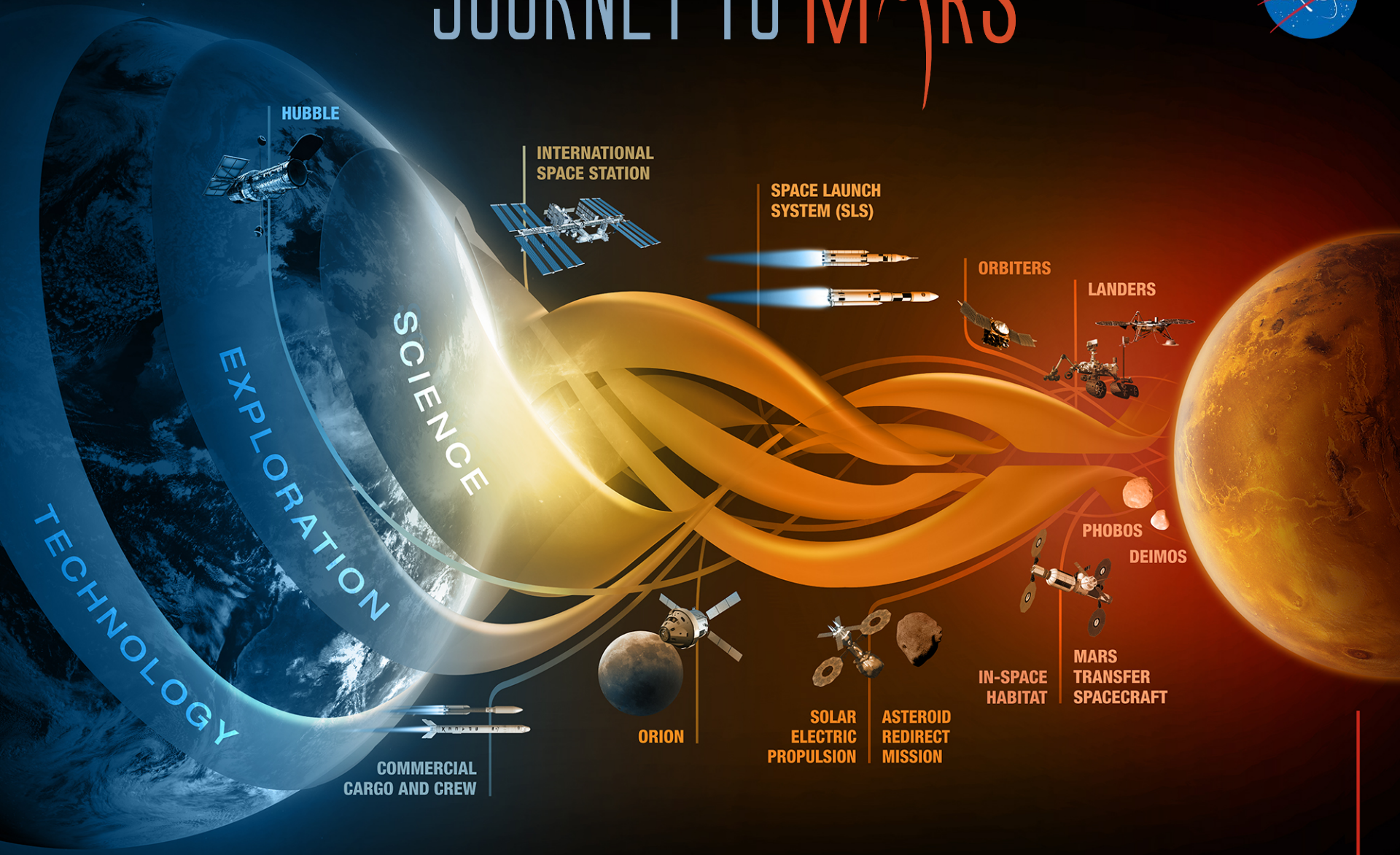
Examine the relationship of national goals to foundational capabilities, robotic activities, technologies, and missions authorized by the NASA Authorization Act of 2010 by assessing them with respect to the set of enduring questions.

Provide findings, rationales, prioritized recommendations, and decision rules that could enable and guide future planning for U.S. human space exploration. The recommendations will describe a high-level strategic approach to ensuring the sustainable pursuit of national goals enabled by human space exploration, answering enduring questions, and delivering value to the nation over the fiscal year (FY) period of FY2014 through FY2023, while considering the program's likely evolution in 2015-2030.

Findings – A Strategy for Sustainability

- The Committee endorsed continuation of human space exploration program, but noted:
  - The nation must decide ***now*** on the nature of that program
  - The only pathways that justify expense, continued investment and risk to crews involved are those that *ultimately place humans on other worlds*
- The pathway principles and decision rules put forth in the report should be adopted (highest priority recommendation)
- A sustainable program of human deep space exploration must have an ultimate, "horizon" goal (Mars)
  - Provides a long-term focus less likely to be disrupted by failures, accidents, and vagaries of the political process and economic scene
  - Mars not achievable with flat funding or with rise at rate of inflation (~2.5%)
- NASA should focus now on the high-priority research and technology:
  - Entry, descent, and landing for Mars;
  - In-space propulsion and power; and
  - Radiation health effects and amelioration

JOURNEY TO MARS



MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT

MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND

MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

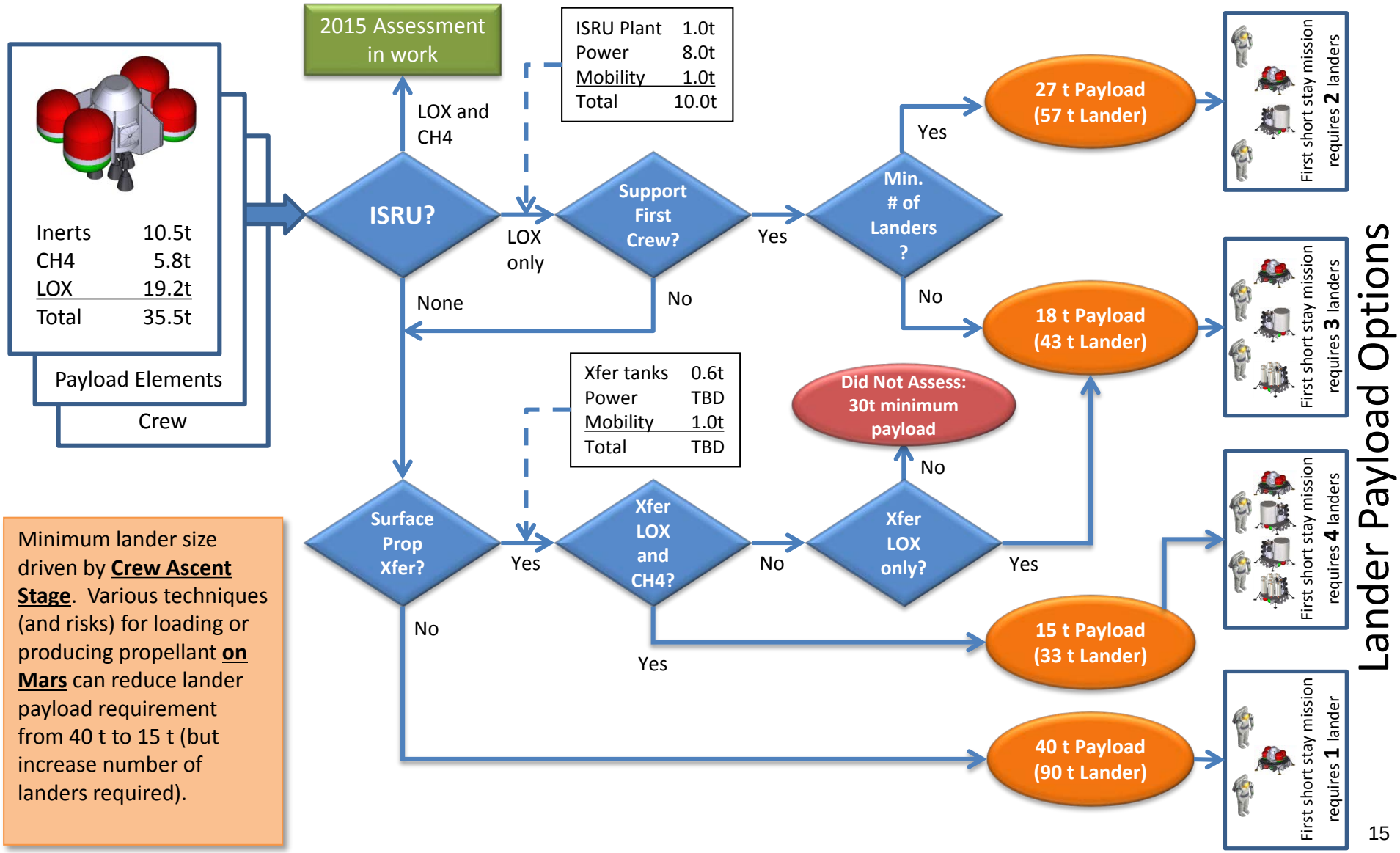
Strategic Principles for Sustainable Exploration

- Implementable in the *near-term with the buying power of current budgets* and in the longer term with budgets commensurate with economic growth*;*
- *Exploration enables science* and science enables exploration*, leveraging robotic expertise for human exploration of the solar system*
- Application of *high Technology Readiness Level* (TRL) technologies for near term missions, while focusing sustained investments on *technologies and capabilities* to address challenges of future missions;
- *Near-term mission opportunities* with a defined cadence of compelling and integrated human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time;
- Opportunities for *U.S. commercial business* to further enhance the experience and business base;
- *Multi-use, evolvable* space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions; and
- Substantial new *international and commercial partnerships*, leveraging the current International Space Station relationships while building new cooperative ventures.

Capabilities for Pioneering Space:
Steps on the Journey to Mars

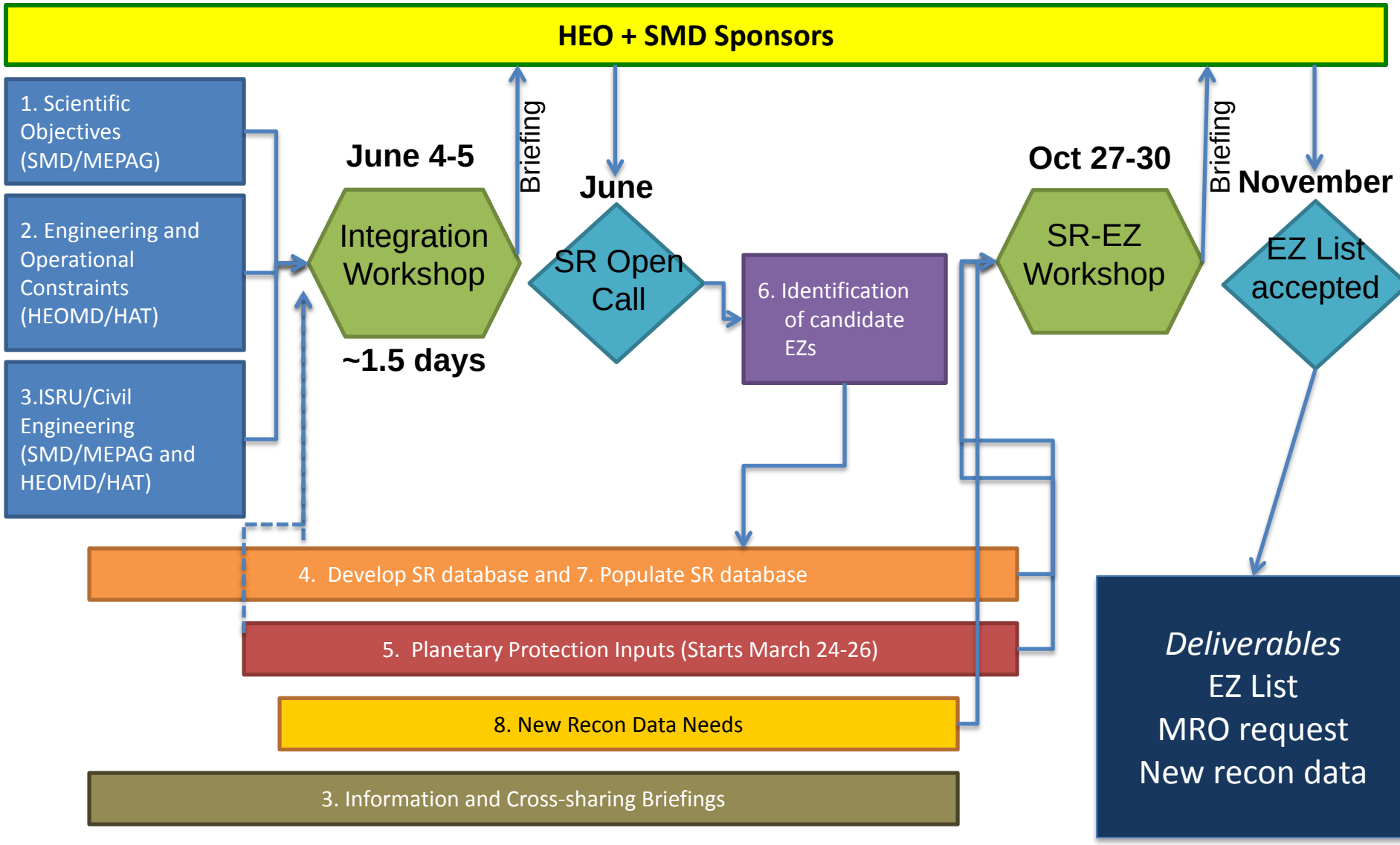
	Capability \ Mission / Location	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Mars Orbit	Mars Moons	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU	Exploratory ISRU		Exploratory ISRU	Operational ISRU & High Power
	Surface Habitat & Mobility					Long Duration	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Earth Monitored	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Frequent EVA	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Long Duration	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration	Long Duration	Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Surface Enhanced	Surface Enhanced
Transportation	Ascent from Planetary Surfaces					Protoflight Use	Operational Capability
	Entry, Descent & Landing				High Mass Pathfinder		Operational Capability
	In-space Power & Prop		Low power	Low Power	High Power	High Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND		EARTH INDEPENDENT		

Largest Indivisible Payload Element and Options for Size of the Lander

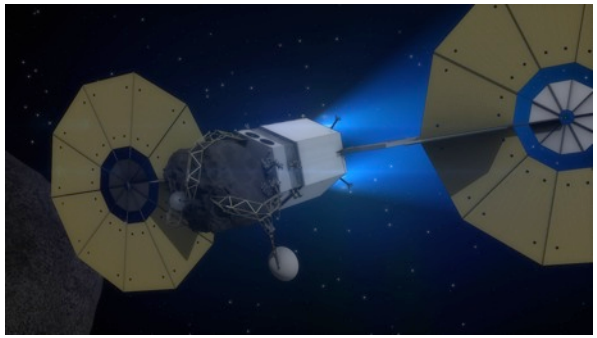


Minimum lander size driven by **Crew Ascent Stage**. Various techniques (and risks) for loading or producing propellant **on Mars** can reduce lander payload requirement from 40 t to 15 t (but increase number of landers required).

2015 Human Landing Site Study

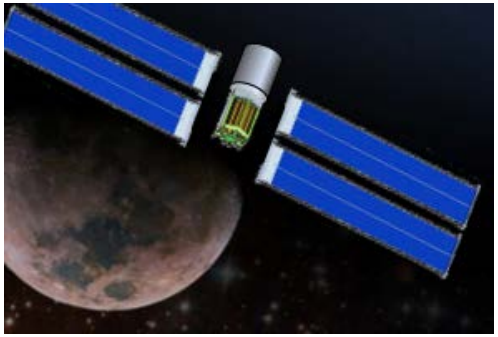


SEP Module Extensibility for Mars



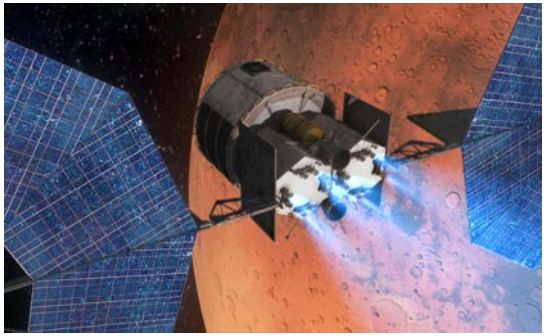
Block 1

- 50-kW Solar Array
- 40-kW EP System
- 10-t Xenon Capacity



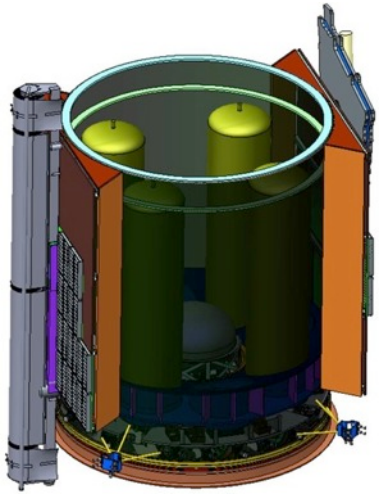
Block 1a (SEP/Chem)

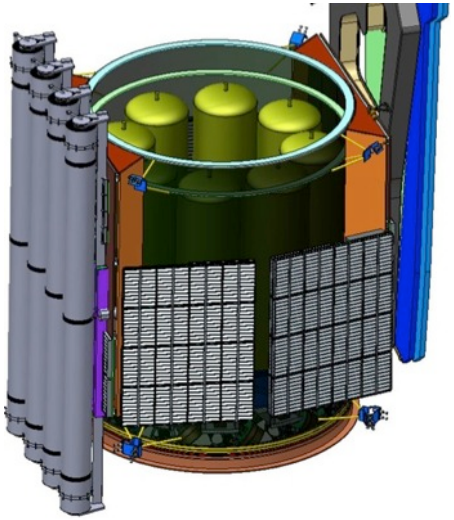
- 190-kW Solar Array
- 150-kW EP System
- 16-t Xenon Capacity

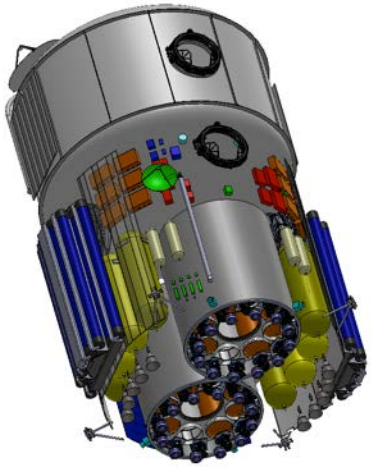


Hybrid

- 250 to 400-kW Solar Array
- 150 to 200-kW EP System
- 16-t Xenon Capacity With Xe Refueling Capability







Foundation of Space Radiation Radiobiology Research

- External review by National Council on Radiation Protection (NCRP), National Academy of Sciences, and HRP Standing Review Panels
- Seven NASA Specialized Centers of Research (NSCOR's)
- Funded research at over 40 US Universities including collaboration with US Department of Energy (DoE)
- Space radiation simulated at the NASA Space Radiation Laboratory (NSRL)
- Partnership with NASA's Space Radiation Analysis Group on transition of risk assessment tools to Operations
- Partnership with National Space Biomedical Research Institute (NSBRI) on acute and cardiovascular risks
- Collaborations with other NASA Programs support an integrated protection strategy across physical and biological solutions

Human System Risk Board (HSRB)
Identified 30 Human Spaceflight Health Risks

Altered Gravity Field

1. Spaceflight-Induced Intracranial Hypertension/Vision Alteration
2. Urinary Retention
3. Space Adaptation Back Pain
4. Renal Stone Formation
5. Risk of Bone Fracture due to spaceflight Induced bone changes
6. Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance
7. Reduced Physical Performance Due to Reduced Aerobic Capacity
8. Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress due to Vestibular / Sensorimotor Alterations associated with space flight.
9. Cardiac Rhythm Problems
10. Orthostatic Intolerance During Re-Exposure to Gravity
11. Adverse Health Effects due to Alterations in Host Microorganism Interaction

Radiation

1. Risk of Space Radiation Exposure on Human Health

Distance from Earth

1. Unacceptable Health and Mission Outcomes Due to Limitations of In-flight Medical Capabilities
2. Risk of Ineffective or Toxic Medications due to Long Term Storage

Isolation

1. Risk of performance decrements due to adverse behavioral conditions

Hostile/Closed Environment-Spacecraft Design

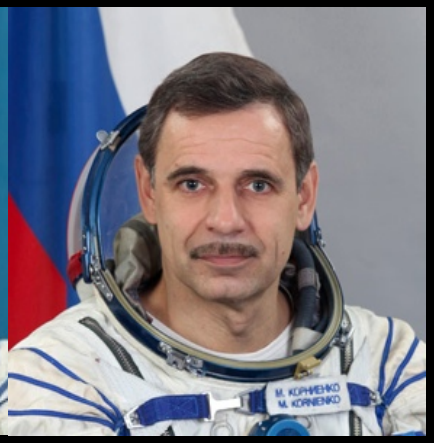
1. Toxic Exposure
2. Acute & Chronic Carbon Dioxide Exposure
3. Hearing Loss Related to Spaceflight
4. Risk of reduced crew performance prior to adaptation to mild hypoxia.
5. Injury and Compromised Performance due to EVA Operations
6. Decompression Sickness
7. Injury from Sunlight Exposure
8. Incompatible Vehicle/Habitat Design
9. Inadequate Human-Machine Interface
10. Risk to crew health and compromised performance due to inadequate nutrition
11. Adverse Health Effects of Celestial Dust Exposure
12. Performance Errors Due to Fatigue Resulting from Sleep Loss, Circadian Desynchronization, Extended Wakefulness, and Work Overload
13. Injury from Dynamic Loads
14. Risk of Altered Immune Response
15. Risk of Electrical Shock

Each risk will be controlled by a NASA standard to protect crew health and safety

ISS One-Year Mission

- 2015 marks the launch of astronaut Scott Kelly and cosmonaut Mikhail Kornienko to the ISS for 12 months – the longest mission ever assigned to a US astronaut
  - Joint US/Russian ISS research includes studies on: ocular health, immune and cardiovascular systems, cognitive performance testing, and effectiveness of countermeasure against bone and muscle loss

Scott Kelly
STS-103, STS-118, ISS 25/26



Kornienko

- HRP study of identical twins astronaut Scott Kelly, and retired astronaut, Mark Kelly
  - Provides unprecedented opportunity to research effects of spaceflight on twin genetic makeup, and better understand the impacts of spaceflight on the human body

Retired astronaut Mark Kelly (left) and his twin brother, astronaut Scott Kelly, who will spend a year on ISS

http://www.nasa.gov/exploration/humanresearch/index.html

Findings: Essential Cornerstones I

The rationales for human spaceflight are a mix of the aspirational and the pragmatic

- The primary rationale for the Apollo program was to demonstrate the technological and ideological supremacy of the United States over the Soviet Union – a conflict which is now over
- Quantification of the value of human spaceflight to the nation today, in terms of economic return or increased quality of life, is difficult.
- This does not mean that there are no benefits: W.B. Cameron wrote *"not everything that can be counted counts, and not everything that counts can be counted"*.

Rationales For Human Spaceflight: Findings

Economic– The NASA human spaceflight program has stimulated economic activity and has advanced development of new products and technologies. It is impossible, however, to develop a reliable comparison of the returns from spaceflight versus other government R&D investments.

Security/Geopolitical--An active U.S. human spaceflight program gives the United States a stronger voice in an international code of conduct for space, enhances U.S. soft power, and supports collaborations

Education and inspiration—Space missions can serve as an inspiration for students and citizens to engage with science and engineering, although the path to becoming a scientist or engineer requires much more than the initial inspiration.

Scientific discovery--The relative benefits of robotic versus human efforts in space science are constantly shifting as a result of changes in technology, cost, and risk.

Human survival--Whether human off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species is a question that can only be settled by pushing the human frontier in space.

Shared destiny and aspiration to explore--Some say it is human destiny to continue to explore space. While not all share this view, for those who do, it is an important reason to engage in human spaceflight.

Findings: Essential Cornerstones II

The level of public interest in space exploration is modest relative to other public policy issues

- Public opinion about space has been generally favorable over the past 50 years, but much of the public is inattentive to space exploration and spending on space exploration is not a high priority for most of the public.
- Stakeholder surveys and public outreach mirror rationales and reflect a permissive policy environment supporting human space exploration

Findings: Essential Cornerstones III

The horizon goal for human space exploration is Mars

- There is a small set of plausible goals for human space exploration in the foreseeable future, the most distant and difficult of which is a landing by human beings on the surface of Mars.

- All long-range space programs, by all potential partners, for human space exploration converge on this goal.

Findings: Essential Cornerstones IV

A program of human space exploration beyond Low Earth Orbit is not sustainable with a human spaceflight budget that increases only enough to keep pace with inflation

- The current program to develop launch vehicles and spacecraft and then to operate them for flight beyond LEO cannot be sustained with constant buying power over time
  - Does not provide the flight frequency required to maintain competence and safety,
  - Does not possess the "stepping-stone" architecture that allows the public to see the connection between the horizon goal and near-term accomplishments, and
  - May discourage potential international partners
- The committee proposed a *pathways approach* that requires the U.S. to settle on a definite pathway to the horizon goal and adhere to certain principles and decision rules to get there

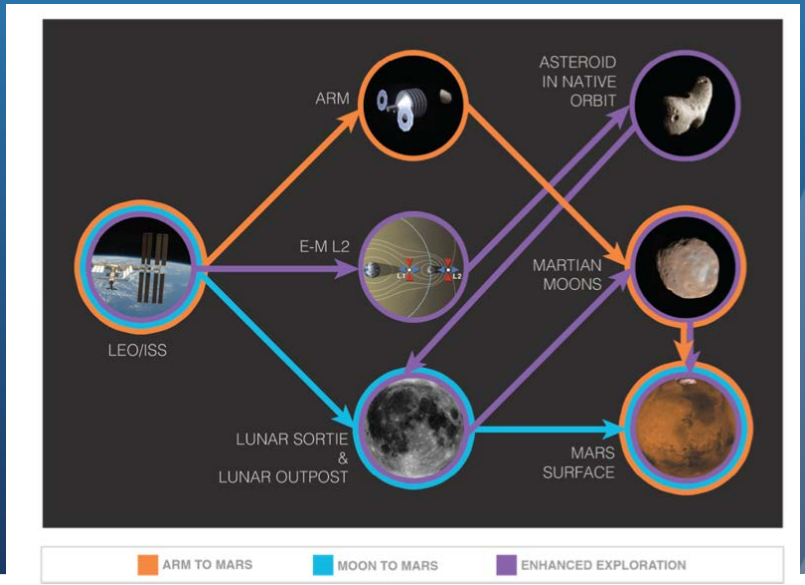
Pathways Approach: I

- Stepping stones: Between LEO and the martian surface are regions of space with stepping stone destinations reachable with foreseeable advances in the state of the art of key capabilities. These include:
  - Cislunar space, which encompasses missions to the Earth-Moon L2 point, lunar orbit, and the lunar surface (both lunar sorties with relatively short stays and lunar outposts with extended stays);
  - Near-Earth asteroids (NEAs) in their native orbits; and
  - Mars, which encompasses a Mars flyby mission as well as missions to the moons of Mars, Mars orbit, and the surface of Mars.
  - Earth-moon Lagrange points.
- Pathways approach in a nutshell:
  - A specific sequence of intermediate accomplishments and destinations normally of increasing difficulty and complexity
  - Leads to an ultimate (horizon) goal with technology feed-forward from one mission to subsequent missions
  - Destinations have cultural, geopolitical, scientific, inspirational, and/or economic value

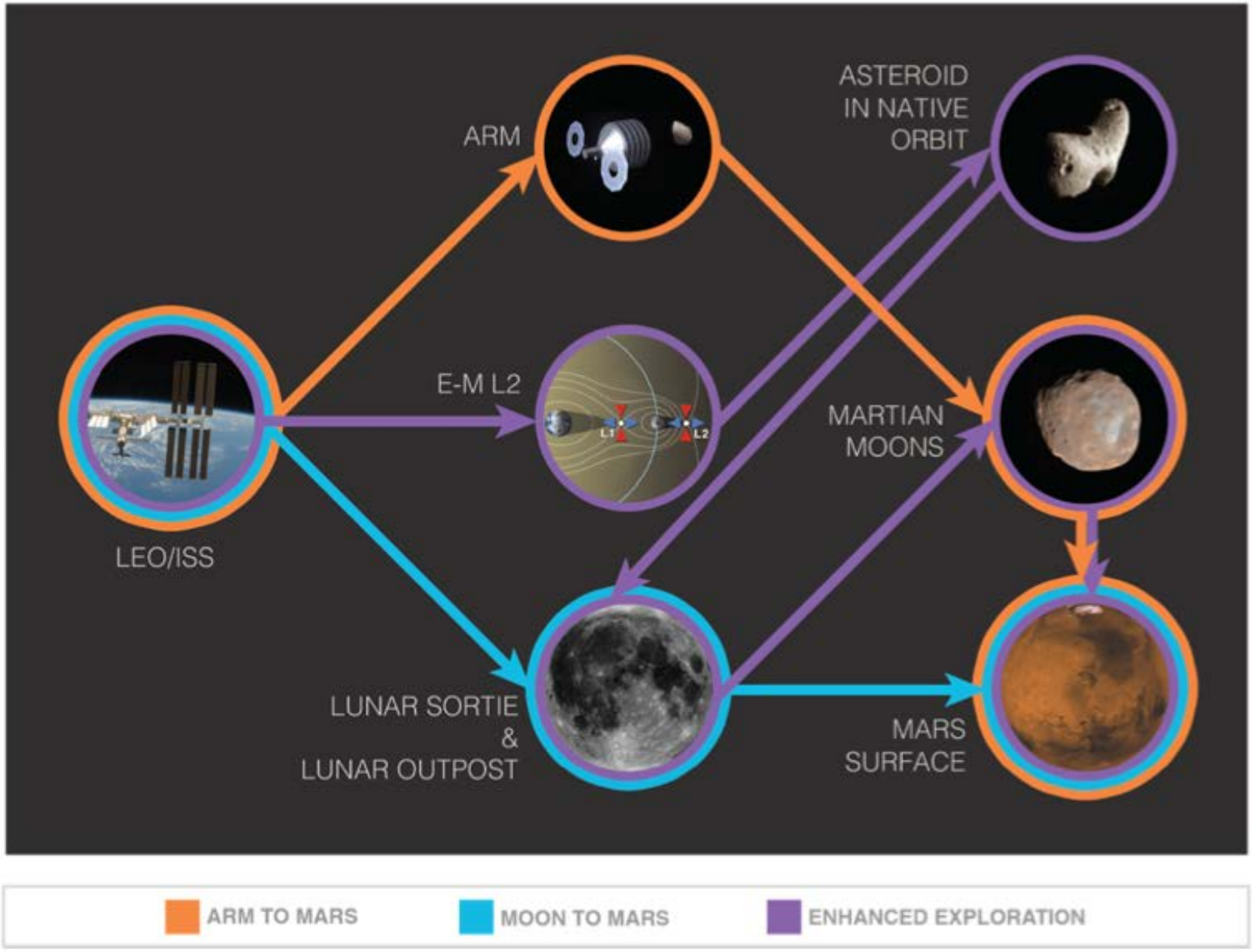
Pathways Approach: II

- NASA can sustain a human space exploration program with meaningful milestones that simultaneously reasserts U.S. leadership in space while allowing ample opportunity for substantial international collaboration when that program:
  - Has elements that are built in a logical sequence, and
  - Can fund a frequency of flights sufficiently high to ensure retention of critical technical capability, proficiency of operators, and effective utilization of infrastructure.

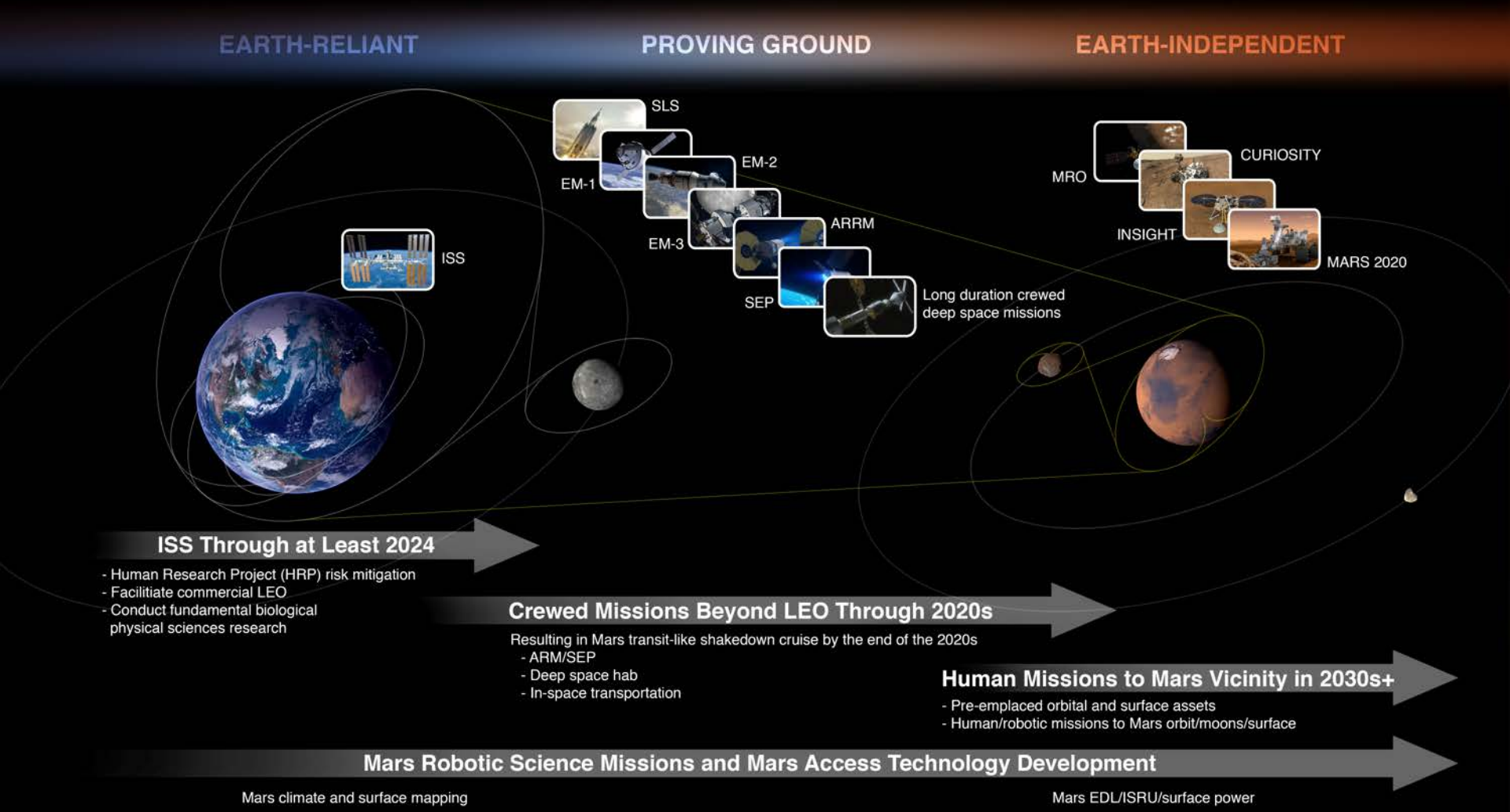
- However, a NASA human spaceflight budget that increases with inflation does not permit a viable pathway to Mars. The program will require increasing the budget by more than the rate of inflation.



3 Possible Pathways (not exhaustive!)



Pioneering Space



Highest Priority Recommendation: Pathway Principles

- Commit to design, maintain, and pursue the execution of an exploration pathway beyond low Earth Orbit toward a clear horizon goal that addresses the "enduring questions" for human spaceflight
  - "How far from Earth can humans go?" – and
  - "What can humans discover and achieve when we get there?"
- Engage international space agencies early in design and development of the pathway on the basis of their ability and willingness to contribute
- Define steps on the pathway that foster sustainability and maintain progress on achieving the pathway's long-term goal of reaching the horizon destination
- *Seek continuously to engage new partners that can solve technical or programmatic impediments to pathway progress*

Pathway Principles II:

- Create a risk mitigation plan to sustain the selected pathway when unforeseen technical or budgetary problems arise. *Such a plan should also include points at which decisions are made to move to a less ambitious pathway or stand down the program.*
- Establish exploration pathway characteristics that maximize the overall scientific, cultural, economic political, and inspirational benefits without sacrificing progress toward the long-term goal, these characteristics being:
  - The horizon and intermediate destinations have profound scientific, cultural, economic, inspirational, or geopolitical benefits that justify public investment;
  - The sequence of missions and destinations permits stakeholders, including taxpayers, to see progress and develop confidence in NASA being able to execute the pathway;

Pathway Principles III:

- Exploration pathway characteristics (continued):
  - The pathway is characterized by logical feed-forward of technical capabilities;
  - The pathway minimizes the use of dead-end mission elements that do not contribute to later destinations on the pathway;
  - The pathway is affordable without incurring unacceptable development risk; and
  - The pathway supports, in the context of available budget, an operational tempo that ensures retention of critical technical capability, proficiency of operators, and effective utilization of infrastructure.

Extensibility of Habitation Systems - Commonality

- **Habitation systems are under study in the EMC and considered the next habitation system following Orion. The new system would serve as the foundation for deep space testing and proto-flight vehicle for smaller/short-duration Mars exploration systems**
- **Commonality can be leveraged across two major classes of vehicles:**
  - Short duration/destination – initial deep-space habitation, Phobos Taxi, logistics carriers, Mars Surface/Phobos Mobility, Mars/Lunar Ascent, and possibly airlocks
  - Long duration – Transit Habitat, Phobos Habitat, Mars Surface Habitat

Hab and logistics carriers constrained by early cargo capability (SLS cargo with crew and EELVs - ~4.6m x 10m)

30 – 60 Days

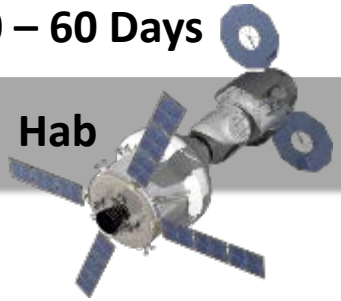
Short Duration

Logistics Carriers

Phobos Taxi

Mars Surface/Phobos Mobility

Mars/Lunar Ascent Vehicle Cabin



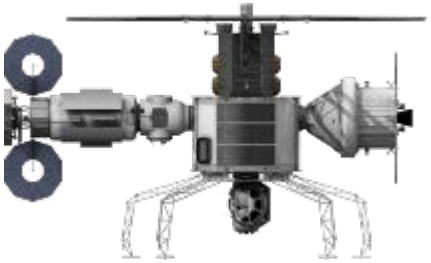
Hab

Transit/Phobos Hab
(docked to hab)

Phobos Hab

Mars Surface Habitat

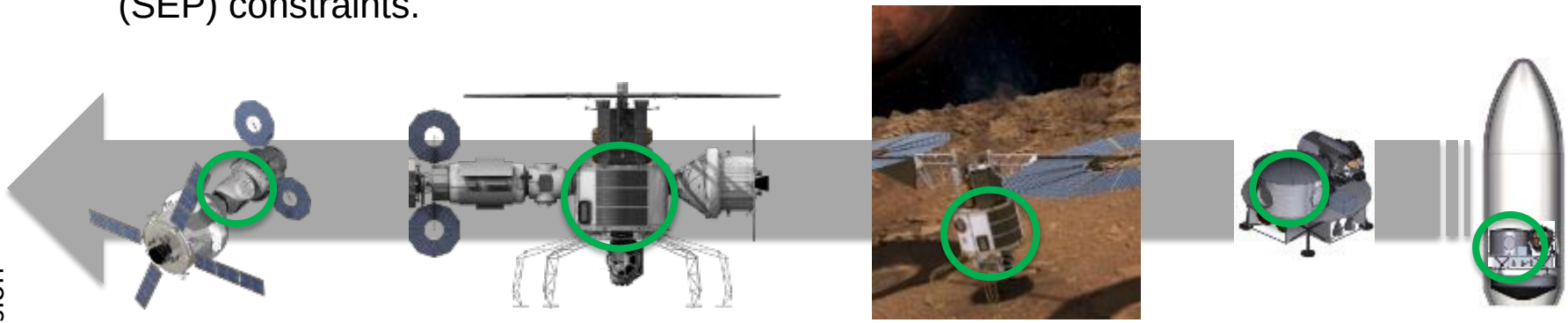
Long Duration



500 Days

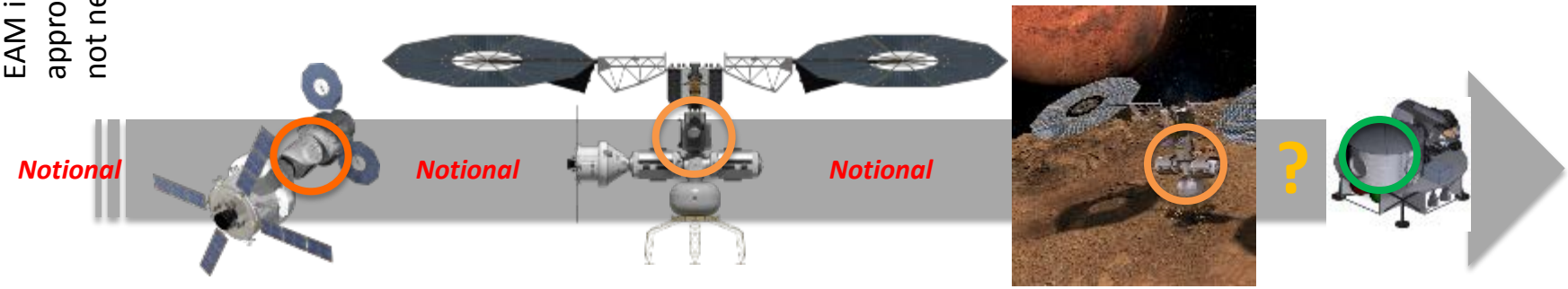
Extensibility of Habitation Systems - Modularity

- **Two paths for long duration habitation modularity**
  - **Right to Left**: Derive common long duration habitat systems and pressure shell commonality options from Mars lander and Phobos habitat transportation system (SEP) constraints.



EAM is common to either approach. Approach decision not needed before 2020

  - **Left to Right**: Build up long duration, in-space habitats from EAM, logistics carriers, and inflatables launched in sections that fit in SLS crew cargo area and aggregated in LDRO



Decision Rules – When problems arise….

- If the appropriated funding level and projected 5-year budget projection do not permit execution of a pathway within the established schedule, then do not start down that pathway.
- If a budget profile does not permit the chosen pathway, take an "off-ramp" (defined as "a less ambitious pathway").
- If the U.S. human spaceflight program receives an unexpected increase in budget for human spaceflight, the increase in funds should be applied to retire rapidly significant technology risks or increase operational tempo
- Give priority to those approaches that solve significant existing technological shortcomings, reduce overall program cost, allow for an acceleration of the schedule, and/or reduce developmental or operational risk.
- If there are human spaceflight program elements, infrastructure, and organizations that no longer contribute to progress along the pathway, the human spaceflight program should divest itself of them as soon as possible.

Pioneering Space is all about Logistical Efficiency

- **Logistics:** procurement, maintenance, transportation of materiel, facilities, personnel
  - Procurement: multiple uses from fewest unique units, technology refresh
  - Maintenance: crew health, self-sufficiency, workforce skill readiness (ops tempo)
  - Transportation: launch, interplanetary transfer, orbit capture, landing/ascent (EDLA)

- **Modularity:** standardized units for flexibility and variety of use
  - Encapsulate complexity with fewest and simplest interfaces
  - Multiple descent/ascent elements, sub-habitats, ISRU and power plants

- **Commonality/Standards:** possession of similar features or attributes
  - Develop units that serve many purposes across a campaign and other markets
  - Common units for Moon and Mars EDLA, space and surface habitats, habitat and rover mobility

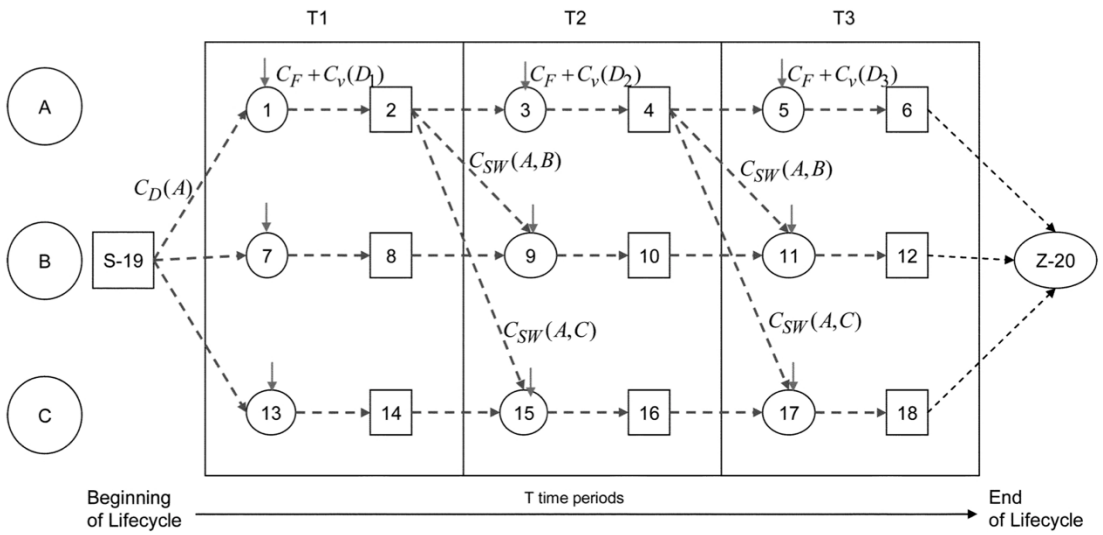
- **Extensibility:** augmenting functionality through minimal additional effort
  - Maturation of capability has growth path to full scale need (no dead ends, open architecture)
  - Precursor mission deploys the first module of an operational system

- **Affordability:** minimize NRE (fewer unique units) & RE (higher production volume)
  - Sacrificing some efficiency (e.g., SWaP) within a unit may increase its use in other applications and thereby gain system-wide efficiency

Designing a Resilient Architecture

Design flexibility into large-scale, complex systems to adapt more easily to change

1. Design a set of potential system configurations
2. Quantify switching costs between these configurations
3. Expand network in time to include chance (circles) and decision (squares) nodes
4. Evaluate minimum cost paths through the network under plausible operational scenarios
5. Modify the set of initial configurations to exploit high-leverage switches



"Time-Expanded Decision Networks (TDN): A Framework for Designing Evolvable Complex Systems," M. Silver and O. de Weck, 2007

Findings: International Collaborations

I. U.S. near-term goals for human exploration are not aligned with those of our traditional international partners (beyond ISS)

Most major spacefaring nations and agencies are looking toward the Moon

U.S. plans are focused on redirection of an asteroid into a retrograde lunar orbit where astronauts would conduct operations with it.

Although the United States is not expected to blindly follow the desires of other nations in shaping its own exploration program, there are a number of advantages to the United States being a more active player in lunar surface operations.

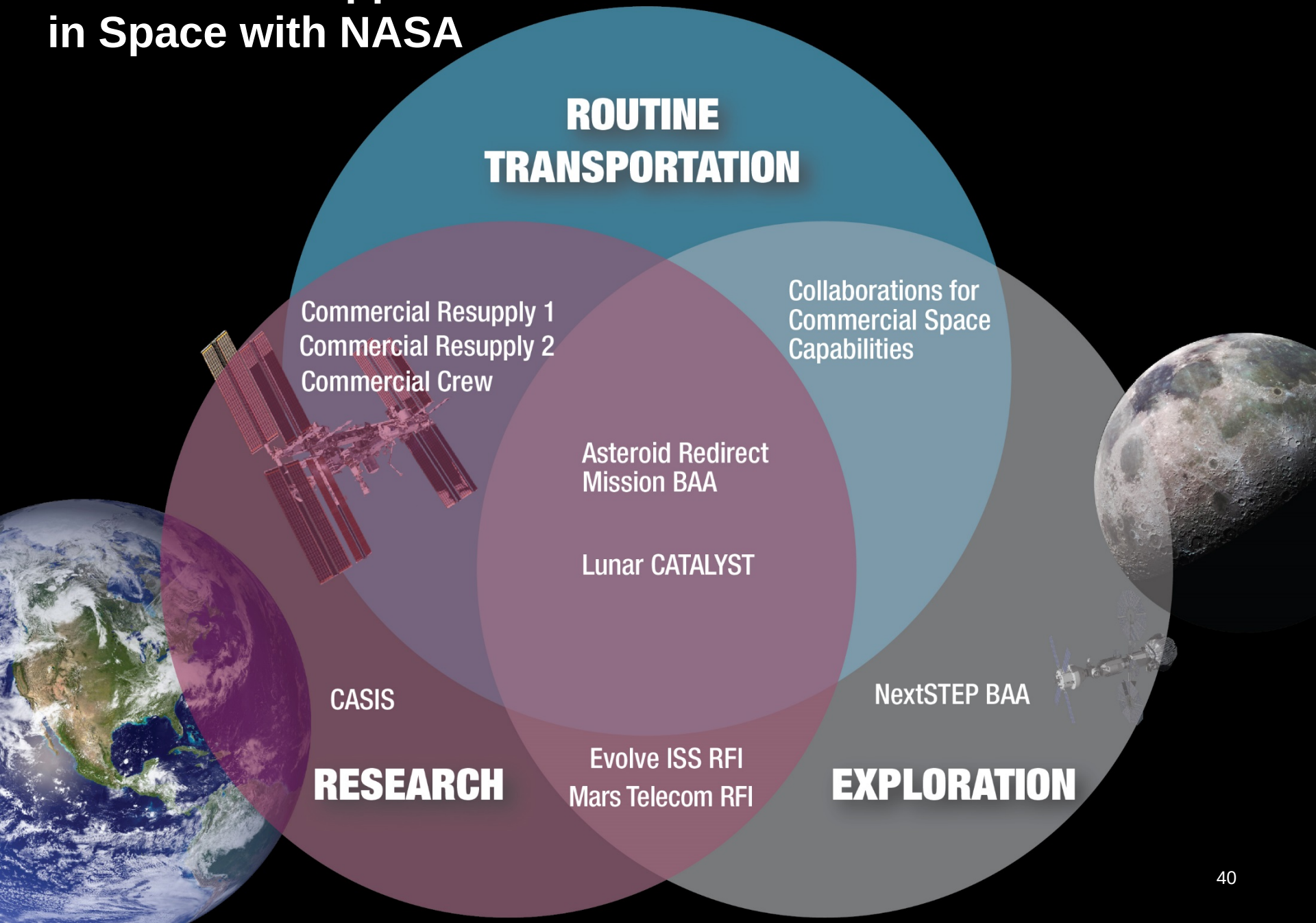
II. Noting the rapid development of China's capabilities in space, it is in the best interests of the US to be open to future international partnerships

- Given the scale of the endeavor of a mission to Mars, contributions by international partners would have to be of unprecedented magnitude to defray a significant portion of the cost.

Findings: Commercial Partnerships

- The report noted:
  - Completion of the commercial cargo launch development program (COTS) and transition to operations
  - The potential reduction in cost associated with new acquisition model
  - The shift of development risk to private sector for new systems
- With regard to longer term considerations, the report is more circumspect
  - The near-term objectives of commercial cargo and crew are to mitigate U.S. dependence on Russia for transport
  - Unclear whether it will reduce costs
  - Has helped stabilize and expand the U.S. industrial base
  - Longer term – the establishment of a space-based economy with human spaceflight as a major component may be possible, but is speculative

Commercial Opportunities in Space with NASA

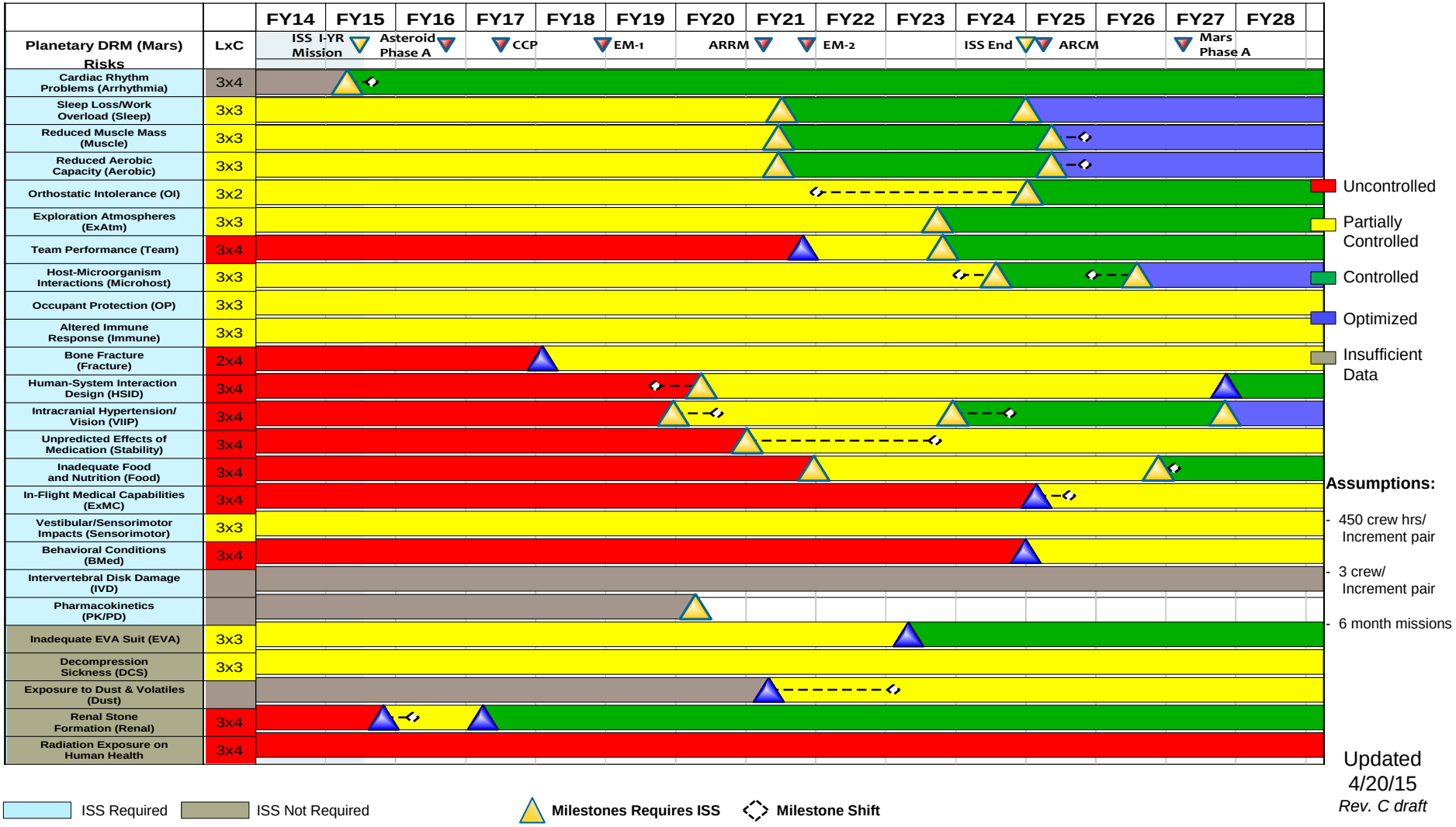


Additional Considerations…

- The report noted that terminating the ISS earlier rather than later may open up a funding wedge for Beyond Earth Orbit exploration that could be time-critical; however it also noted that doing so would adversely impact commercial space transportation providers and hopes for a developing in-space economy in LEO
  - The Committee recommended near-term discussions with International Partners regarding implications of continuation/termination of the ISS
- Commercial approaches to and international collaboration in Beyond Earth Orbit exploration will have to greatly exceed previous levels of cost sharing (or reduction) in order to substantially impact budget profiles for various pathways

Human Exploration and Operations

Human Research Program: Integrated Path to Risk Reduction



Updated 4/20/15
Rev. C draft

ISS Technology Demonstration Plan

Capability Gap	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28
ECLSS															
Reliable CO2 Removal + lower ppCO2	CDRA-5		sorbent exp		CDRA upgrades			next gen system							
Smaller, simpler O2 Gen							next gen OGA								
High pressure O2 for EVA & medical use															
Reliable urine processing ~85% recovery			alt pt	ISS UPA upgrad			next gen UPA								
Reliable water processing w/ reduced expendables				MF bed mod			cat reactor mod								
Common biocide with on orbit replenishment															
Waste management						UWMS			HMC						
Additional O2 recovery from CO2 >75%									>75% recovery						
Additional water from brine >85% recovery					demo candidates				brine processor						
Logsitics Reduction				REALM				laundry							
Environmental Monitoring															
Trace Gas (on orbit, no grab sample return)	AQM				SAM										
Targeted Gases (fire products, NH3, hydrazine)							saffire								
Water (individual compounds)			suite												
Microbial (ID & qty species)				COTS		Expl PCR									
Major Constitutents (small, no maintenance)					SAM	MPAM (ISS & Orion)									
Particulates				aerosol sampler			particulate monitor								
Acoustic (automated, alerting, no crew time)					tech demo		operational								
EVA															
PLSS & Pressure Garment ug test									PLSS 3.0						
EMU upgrades															
Fire Safety and Response															
Emergency Mask (single cartridge)	dual				single										
Contingency Air Monitor (overlap with targeted gas)								Saffire							
Smoke Eater															
Water Mist PFE			ISS size												
Crew Health & Performance Technologies															
Exercise Equipment			Orion device					Exploration device							
Medical Equipment						ESMD									
Food System									Adv food system						
Thermal (including Cryo)															
ZBOT (Phases 1-3)				Phase I		Phase 2				Phase 3					
Phase Change Material				wax		water									
Variable Heat Rejection radiators, single loop fluids															
Power & Energy Storage															
Solar arrays				ROSA			30 kW Common agency array								
Energy Storage				Li ion batt		Regen fuel cell									
Comm & Navigation															
High speed comm/internetworking	DTN & OPALS, SCAN TB						ISS terminal?				TDRS upgrades				
Position, navigation, and timing				NICER/SEXTANT											
Structures & Materials															
Materials/In-space manufacturing		3D print (plastic)			mtls reuse		"fab lab"								
Structures & Health Monitoring			BEAM												
Radiation Monitoring & Shielding		REM		Adv neutron spectrometer											
ISRU (trash processing, resource prospecting, in-situ manufacturing) Plans under construction.															
Autonomous Operations		TOCA	AMO EXPRESS			ISS crew autonomy 2.0									
Automated Rendezvous & Docking				RAVEN											
Robotics															
Robotic refueling		RRM2			RRM3 (includes cryo mass gauge)										
Free flyer robots (IVA & EVA)			IVA			EVA									
Human assist robots	Robonaut			Robotic Caretaker											
Telerobotics															

no committed funding
some $, but insufficient funding for ISS demo
sufficient funding to ISS demo

Funded ISS demo
Proposed ISS demo (not yet funded)

LEO Commercialization

From Steering Committee Consensus

Vision: Sustained economic activity in LEO enabled by human spaceflight, driven by private and public investments creating value and benefitting Earth through commercial supply and public and private demand

Goals

1.0 LEO commercialization enabled by leveraging ISS

- *User-friendly ISS process improvements*
- *Maximize throughput*
- *Demonstrate & communicate value proposition of ISS*
- *Foster "success stories"*
- *Utilize more commercial acquisition strategies*

2.0 The policy and regulatory environment promotes commercialization of LEO

- *Establish interagency working group to address policy and regulatory issues*
- *Investigate economic cluster potential*
- *Address barriers such as IP retention, liability, ITAR*

3.0 A robust, self-sustaining, and cost effective supply of US commercial services to/in/from LEO accommodates public and private demands

- *Leverage NASA NEXTSteps BAA studies and follow-on to enable commercial LEO capabilities*
- *Enable Earth-similar laboratory capabilities for ISS that can transition to commercial platforms*
- *Transition from NASA-supplied to commercially-supplied services and capabilities once available*

4.0 Broad sectors of the economy using LEO for commercial purposes

- *Establish consortia for potential high-payoff, market-enabling microgravity applications with public and private funds to support development (e.g. protein crystallization, exotic fibers, lightweight alloys, 3D tissues)*
- *Establish commercial LEO utilization university curriculum and programs*

A Year Later: How does the Pathways report align with NASA activities? Major Points:

- The HSF Committee endorsed the continuation of human spaceflight program(s) and deep space exploration, with a horizon goal of Mars
- Further, such a program should advance U.S. leadership and be worthy of the investment and inevitable loss of life. This means ultimately placing humans on other worlds.
- Committee supported increase in funding (roughly on the order of rate of inflation + 2-3%)
  - Mitch Daniels – Committee Co-Chair, to House SST Committee – "a drop in the bucket")
  - NASA – budget will require "moderate increase" in out years
  - Dr. John Holdren (President's Science Advisor) – "Eventually, yes, between now and the 2030's we would need to ramp up the budget…"
- Committee pointed out the need for international and commercial teaming and cost-sharing on a large scale

Alignment (cont'd)

- Committee supports "stepping stone" approach with "feed-forward technology development"
  - NASA uses stepping stone approach; calls feed-forward "extensibility"
- Committee warns about funding levels vs. operational requirements for SLS; points out that launch cadence is not commensurate with safety.
  - NASA has called for 1X/year "necessary requirement"
- Report calls for near-term technology investment; provides a prioritized list of development
  - NASA has list and is conducting trades; many ((but not all) of the items overlap

Where NASA and NRC are not aligned…

- China (U.S. law)
- Committee didn't "pick" a pathway but raised questions about…
  - Asteroid Retrieval Mission (last briefed in early 2014)
  - Lunar surface operations (base)
    - International Partner interests
- Budget implications
  - Committee found increase in national investment is needed as soon as possible
  - Committee found that Mars was not achievable unless investment followed rate of inflation plus ~2-3%
- Divestiture of unneeded assets
  - Pointed out in other NRC reports; politically difficult

Moving toward alignment…?

- Report calls for pathways approach - goal is <u>sustainability</u>
  - DRM-type logic v NASA approach (evolvable, capabilities-based, resilient); however –
    - Decision rules call for (a) "dropping down to another, less difficult approach" ("off-ramps") or (b) terminating program when these represent unacceptable development risk or "break the budget"
      - Strong similarities to "resilient architecture"
      - Need to better understand scenarios and switches
- NASA's approach is 'capability-based' …goal is <u>sustainability</u>
  - Budgetary constraints
  - Policy environment
  - Time (a program on the order of **multiple** decades, rather than a decade)
  - Uses international partners and commercial capabilities were appropriate. Allows for dependency on others for key capabilities.

Some Final Thoughts

- The aggregate value of the practical benefits and aspirational goals related to human space exploration justify our national investment in and continuation of the program, toward Mars
- Given the complexity of the challenges before it, NASA must evolve – and is evolving
  - Will require NASA to divest what it doesn't need or can acquire through other means at lower cost, or can partner for
  - NASA must *harvest wisely* – can't do everything 'in-house'
    - Turn over every rock – industry, tech development, international collaboration, new acquisition models
    - Must challenge assumptions and sacred cows - be willing to let go of the past but retain unique core capabilities - a tough balancing act!
- <u>Sustainability</u> is the goal, not any particular architecture – those should be evaluated on their merits, as they contribute to that goal

Summary Observations

- **NASA's long-term human spaceflight objective is to "extend human presence into the solar system and to the surface of Mars" (2011 NASA Strategic Plan)**
- **Sustainability is the central idea in NASA's approach, and why we implement the journey to Mars with a pioneering approach**
- **A sustained program requires:**
  - Resilient architectures (the Evolvable Mars Campaign vs a DRM)
  - Robust and evolvable access to space (SLS & Orion)
  - Near term activities that help to understand risks and provide measurable evidence of progress in human spaceflight (ISS technology and human health risks, SLS/Orion with a series of exploration missions with measurable objectives)
  - In-space transportation, AR&D for cargo and crew missions (ARM/SEP and SEP/Chem hybrid concepts)
  - Knowledge of Mars and access to Mars surface (current and future robotic Mars missions)
- **All of these are features of NASA's current programs and investment strategy – our current programs make sense in this strategic context**
- **We progress at the rate funding, technologies, and partnerships allow**

NASA