Human Research Gaps for Moon and Mars

Steering Committee for a Science Strategy
for the Human Exploration of Mars

David Baumann
Director, Human Research Program
April 25, 2024

HRP Presentation to the NAS

- HRP Overview
- Lunar and Mars Gaps
- Research to Get to Mars
- Research to Do on Mars

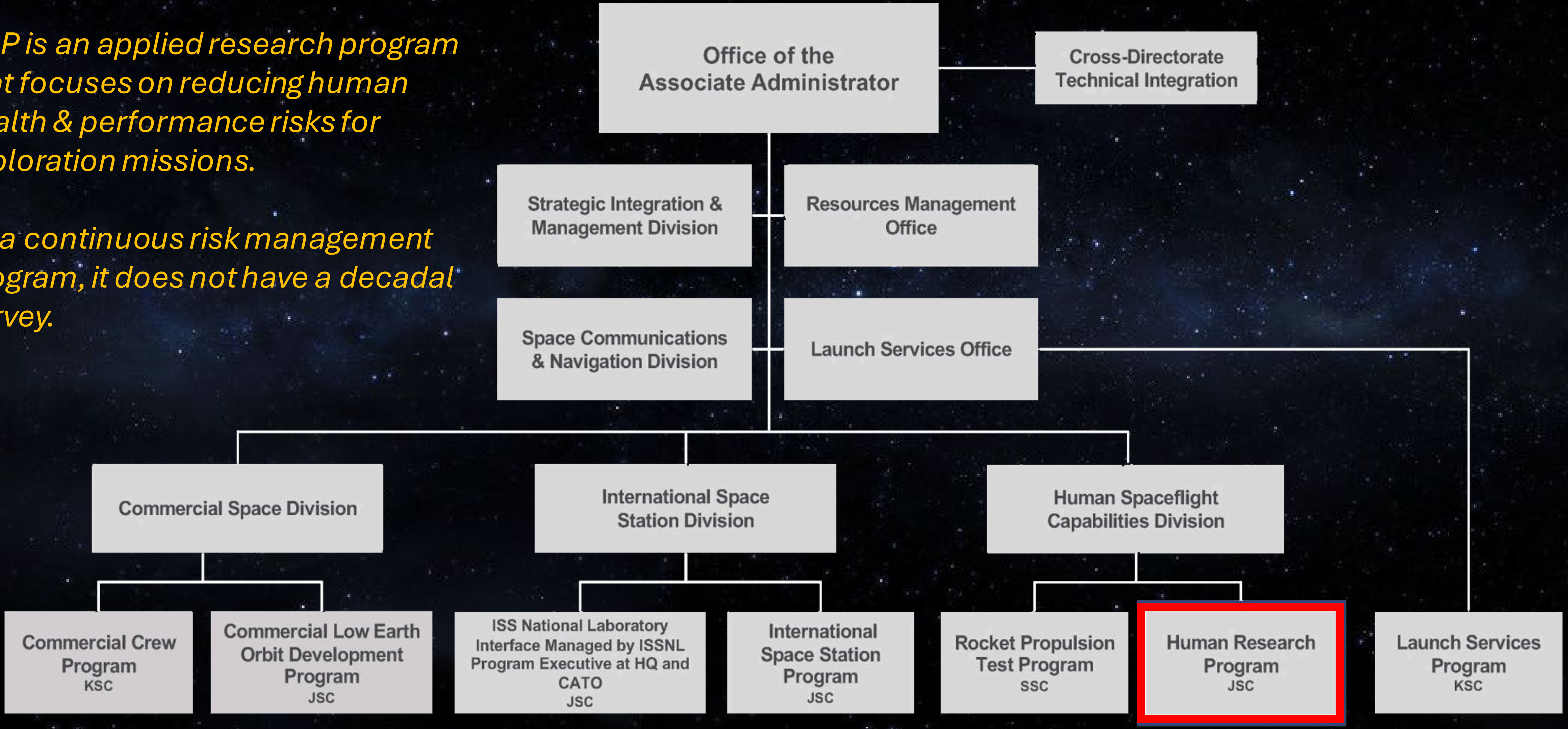
Human Research Program Mission

To enable space exploration beyond low Earth orbit by reducing the risks to human health & performance

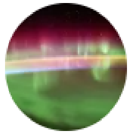
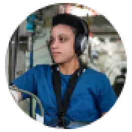
Space Operations Mission Directorate

HRP is an applied research program that focuses on reducing human health & performance risks for exploration missions.

As a continuous risk management program, it does not have a decadal survey.

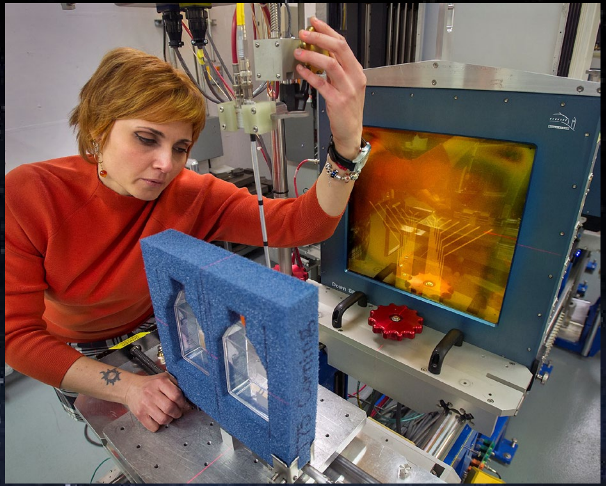


HRP Elements Overview

	**Exploration Medical Capability**	Pushes the boundary of space medical systems to help take care of current and future astronauts.
	**Human Factors and Behavioral Performance**	Characterizes and manages behavioral health effects of long-duration space missions
	**Human Health Countermeasures**	Assesses the effects spaceflight has on the human body and develops safeguards to deal with those changes.
	**Space Radiation**	Ensures that crewmembers can safely live and work in space without exceeding acceptable radiation health risks.
	**Research Operations and Integration**	Plans, integrates, and implements services for HRP research in Earth-based simulations, the International Space Station, and other platforms.


National Aeronautics and Space Administration
NASA
Human Research Program
STEPS TO MARS
EARTH:
Simulated spaceflight hazards in Ground Analogs | :envihab | Antarctic Stations | NEK | HERA | Space Radiation Lab
LOW EARTH ORBIT:
International Space Station – A unique testbed to study micro-gravity and environment hazards, with varying mission durations
LUNAR MISSIONS:
Decreasing Earth-dependence around and on the lunar surface. Provides insight into deep space radiation, behavioral health, and gravity transitions

Steps to Mars: Ground Analogs



Steps to Mars: LEO Spaceflight Missions

Increment 69

Mar 2023 to Sep 2023

Increment 70

Sep 2023 to April 2024

Frank Rubio

>1 year in space
Sep 2022 – Sep 2023

Steps to Mars: Commercial Space Missions

SpaceX Inspiration4

September 16-18, 2021

Axiom 2

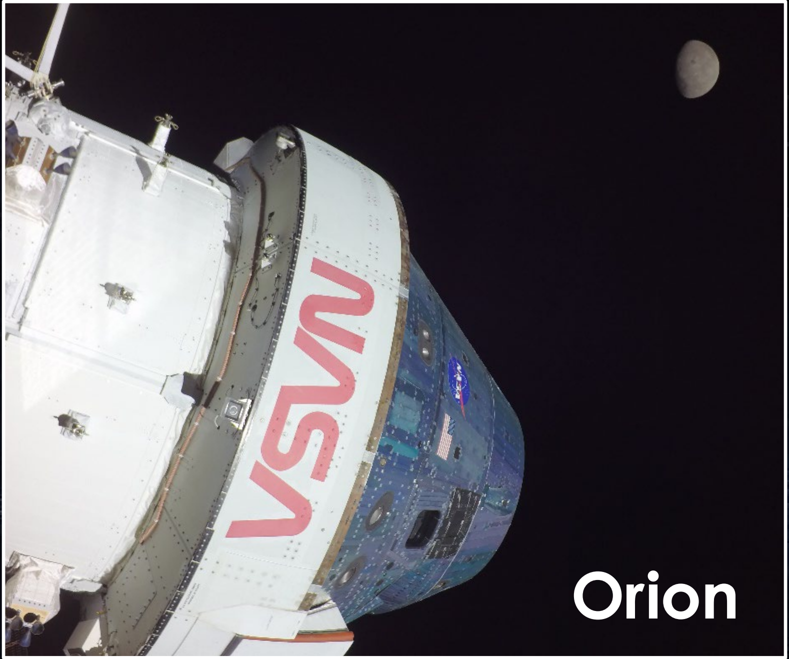
May 21 – May 31, 2023

Axiom 3

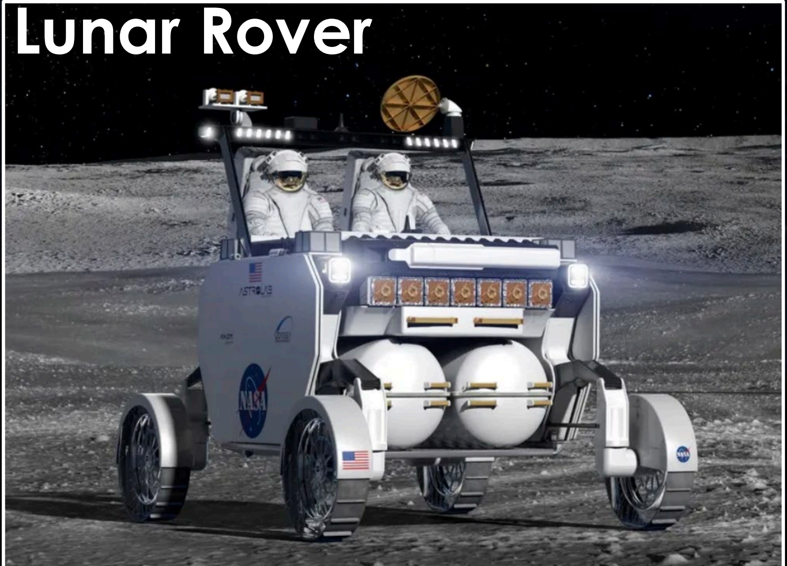
Jan 18 – Feb 9, 2024

Steps to Mars: Commercial LEO Destination Partners

Steps to Mars: Artemis



Orion



Lunar Rover

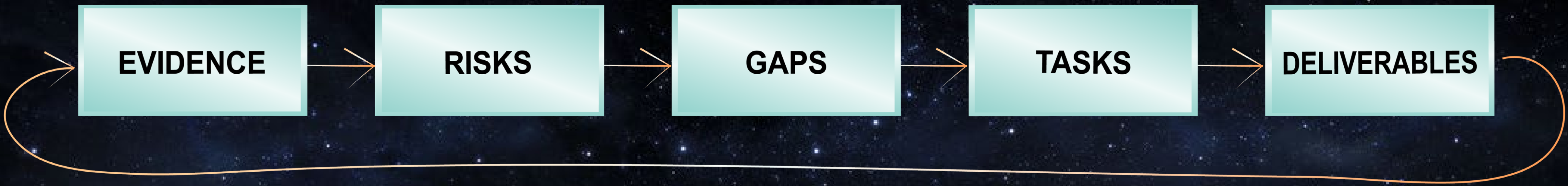
Human Landing System

Gateway

Spacesuits

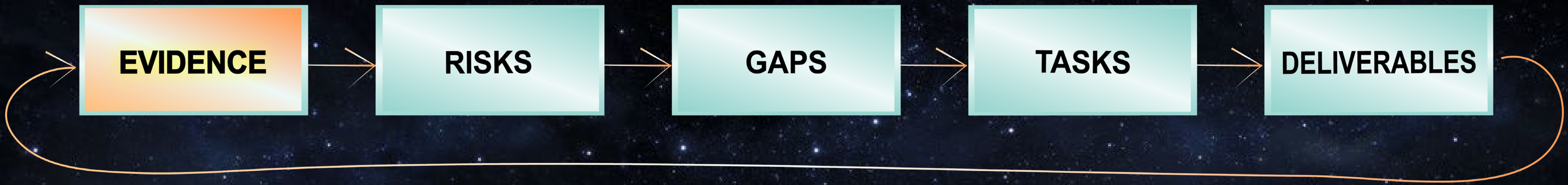
https://humanresearchroadmap.nasa.gov/

HRP’s Applied Research Program Architecture



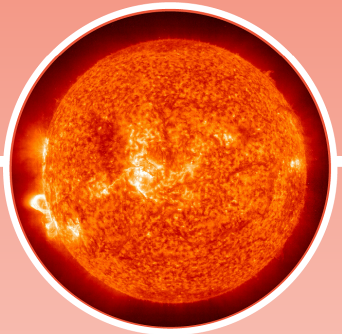
Continuous Risk Management

HRP’s Applied Research Program Architecture



Continuous Risk Management

Evidence: Hazards and Risks of Human Spaceflight



Space Radiation

- Radiation Carcinogenesis
- Non-Ionizing Radiation

Isolation & Confinement

- Inadequate psychosocial adaptation within a team
- Adverse cognitive or behavioral conditions

Distance from Earth

- Inflight medial conditions
- Inadequate human systems integration architecture
- Inadequate food and nutrition
- Ineffective or toxic medications

Lack of Gravity

- Reduced muscle size
- Bone fracture
- Sensorimotor alterations
- Host-microorganisms interactions
- Orthostatic intolerance
- Cardiac rhythm problems
- Renal stone formations
- Reduced aerobic capacity
- Cardiovascular adaptions
- Urinary retention
- Crew egress
- SANS

Hostile/Closed Environment

- Toxic exposure
- Hypoxia
- Decompression sickness
- Celestrial dust exposure
- Carbon dioxide exposure
- Electrical shock
- Sleep loss
- Hearing loss
- Altered immune response
- Reduced EVA performance
- Injury from dynamic loads

HRP Evidence Reports for Individual Risks (Examples)

https://humanresearchroadmap.nasa.gov/Evidence/

Risk of Ineffective or Toxic Medication During Long-Duration Exploration Spaceflight

Evidence Report:

Risk of Ineffective or Toxic Medication During Long-Duration Exploration Spaceflight

Human Research Program

Exploration Medical Capability (ExMC) El

Approved for Public Release: December 20, 2023

Evidence Report:

Risk of Inadequate Human-System Integration Architecture

Evidence Report:

Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload

Evidence Report:

Risk of Spaceflight Associated Neuro-ocular Syndrome (SANS)

Institute of Medicine
Review of HRP Evidence Reports in starting in 2008

Review of NASA's
Human Research Program
Evidence Books

A Letter Report

Committee on NASA's Research on Human Health Risks

Board on Health Sciences Policy

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OF THE NATIONAL ACADEMIES

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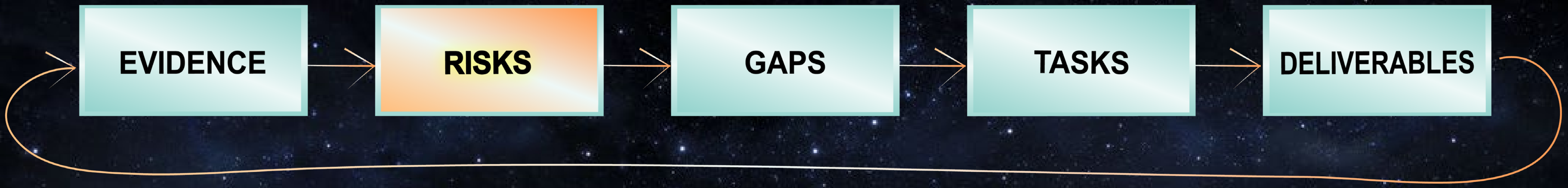
www.nap.edu

HRP's Applied Research Program Architecture



Continuous Risk Management

Continuous Risk Management for the Human System

Human System Risk Board (HSRB)

Human Research Program

- Research Focus
  - Risk Reduction
  - Standards development

Human System Risk Board

research

requirements

evidence

approaches

Health and Medical Technical Authority

- Operational Focus
  - Risk owner
  - Standards owner

HSRB Risk Ratings (HRP "requirements")

- **High Priority Mitigation target** (red)
- **Medium Priority Mitigation target** (yellow)
- **Low Priority Mitigation target** (green)


P.S.I.

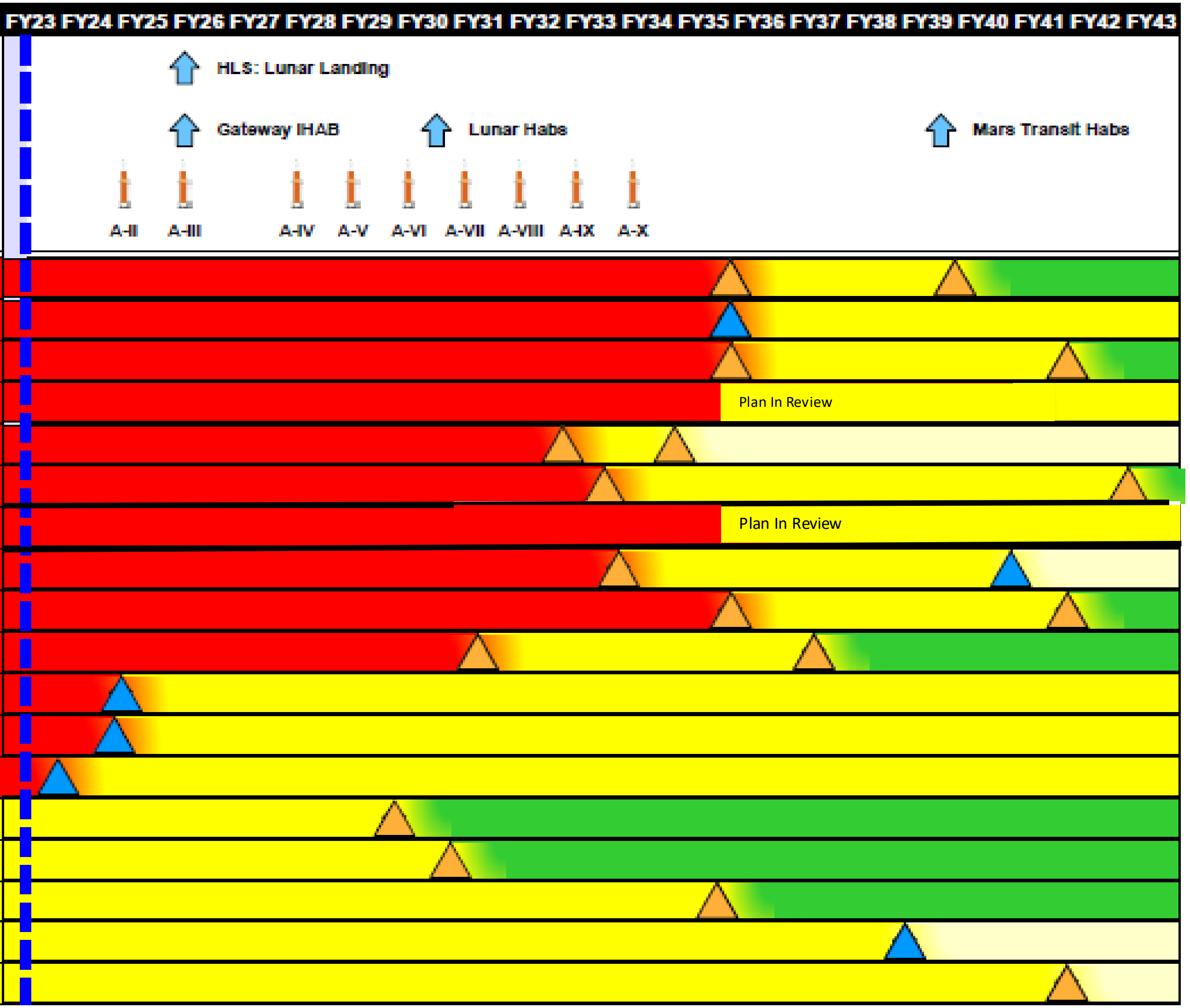

P.S.I.

Mars Path to Risk Reduction

High Priority
Medium Priority
Low Priority

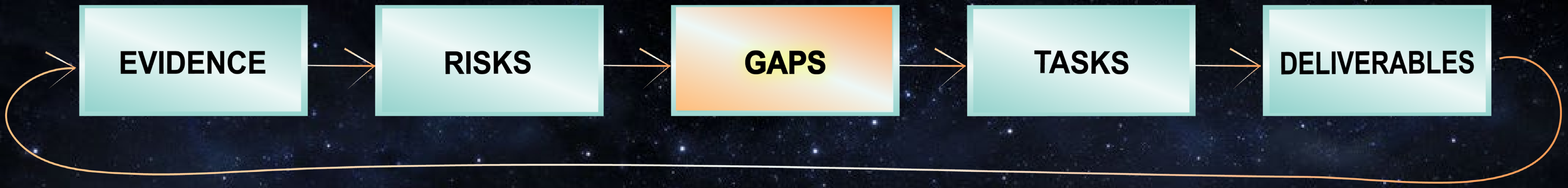
HRP Mars iPRR PPBE25 BASELINED

Unique ID	Exploration DRMs Exploration Mission Milestones (HRP Delivery Dates) RISKS	Artemis Launche LxC
1	Spaceflight Associated Neuro-ocular Syndrome (HHC-SANS)	3x4
2	Celestial Dust Exposure (ExMC-Dust)	4x4 *
3	Cardiovascular Adaptations (HHC-Cardiovascular)	4x4 *
4	Cognitive or Behavioral Conditions (HFBP-BMed)	5x3 *
5	Injury from Dynamic Loads (HFBP-Dynamic Loads)	3x4
6	Bone Fracture (HHC-Bone Fracture)	4x4 *
7	Team Performance Decrements (HFBP-Team)	3x4
8	Human Systems Integration Architecture (HFBP-HSIA)	5x3 *
9	Injury Due to EVA Operations (HHC-EVA)	3x4
10	Inadequate Food and Nutrition (HHC-Food and Nutition)	3x4
11	Medical Conditions In-Mission Long Term Health (ExMC-Medical Conditions)	5x4 *
12	Ineffective or Toxic Medications (ExMC-Pharm)	5X3*
13	Renal Stone Formation (ExMC-Renal Stone)	4x4*
14	Altered Immune Response (HHC-Immune)	3x3
15	Host-Microorganism Interactions (HHC-Microhost)	3x3
16	Vestibular Sensorimotor Impacts (HHC-Sensorimotor)	4x2 *
17	Space Radiation Carcinogenesis (SR-Carcinogenesis)	3x3
18	Sleep Loss and Circadian Misalignment (HFBP-Sleep)	3x3



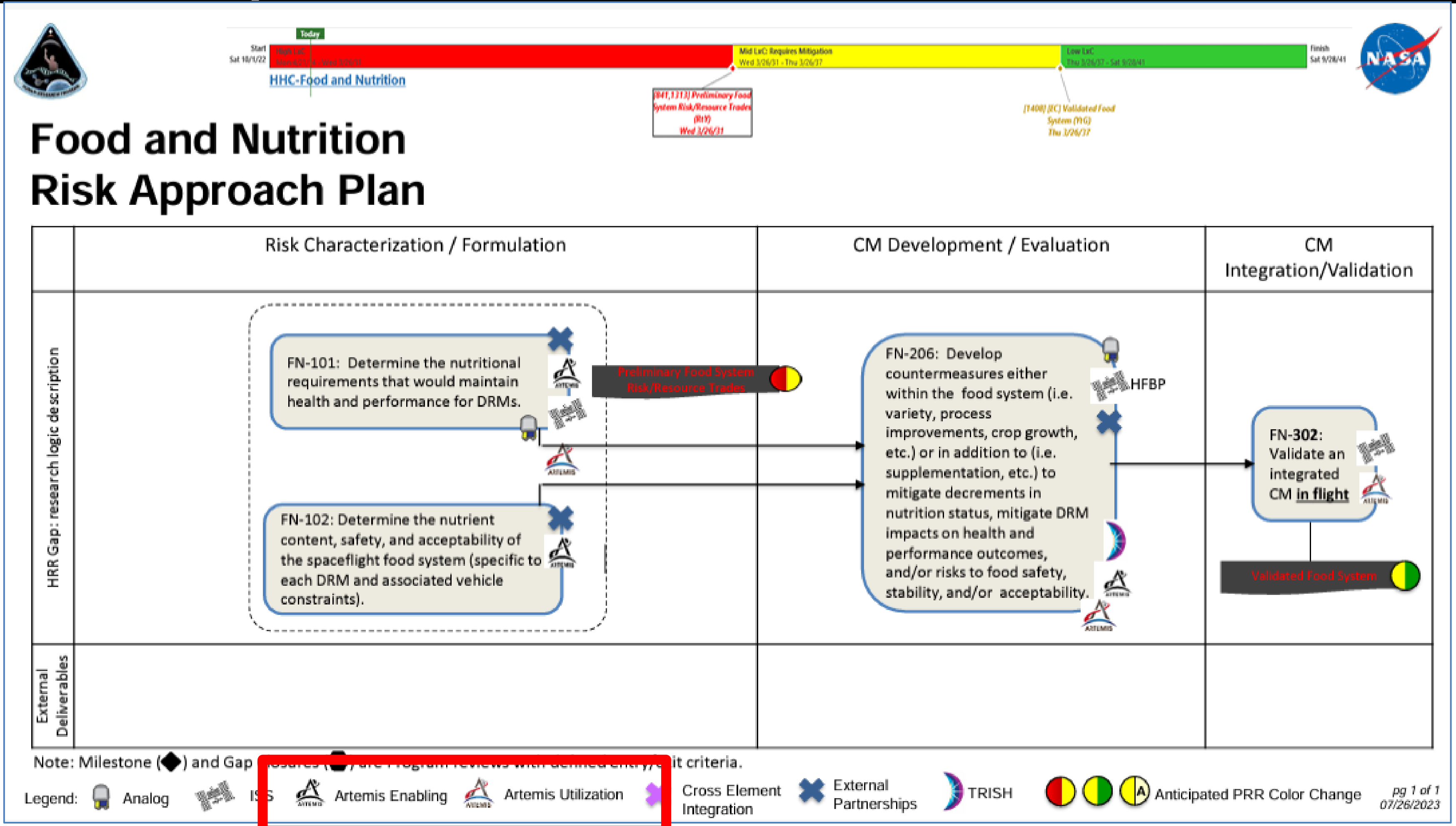
Risk Class: ISS Required
Completed (PRR-Color Change) Shift
Optimized
* (Asterisk) Updated to New HSRB LxC 5x5 Scale
Risk Class: ISS Not Required
High LxC
Insufficent Data
Milestone: Requires LEO Platform
Mid LxC: Requires Mitigation
Exploration Mission Milestone
Ground Based: Milestone
Mid LxC: Accepted
Mission Date
Anticipated (PRR-Color Change) Shift
Low LxC

HRP's Applied Research Program Architecture



Continuous Risk Management

Decomposition of Human Health Risks into Research Gaps
Complete list of Gaps is in BACKUP

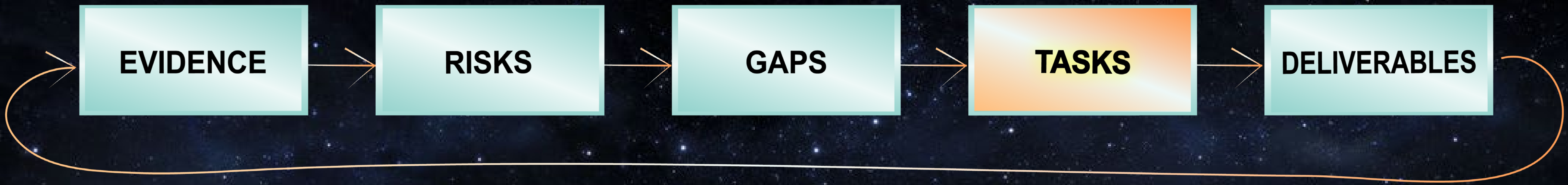


Artemis Enabling = Lunar Gaps
Artemis Utilization = Mars Gaps

Top Crew Health and Performance System Capability Gaps for Mars

- Earth-Independent Human Operations
- Mars Duration Food System
- Mars Duration Effects on Human Physiology
- Risk Mitigations for Vehicle Atmospheres
- Computational Injury & Anthropometric Models
- Exploration Exercise Countermeasures
- Understanding Individual Variability in Spaceflight
- Sensorimotor Countermeasures

HRP's Applied Research Program Architecture



Continuous Risk Management

Top Crew Health and Performance System Capability Gaps for Mars

Earth-Independent Human Operations

Mars Duration Food System

Mars Duration Effects on Human Physiology

Risk Mitigations for Vehicle Atmospheres

Computational Injury & Anthropometric Models

Exploration Exercise Countermeasures

Understanding Individual Variability in Spaceflight

Sensorimotor Countermeasures

Risks Increases with Distance from Earth

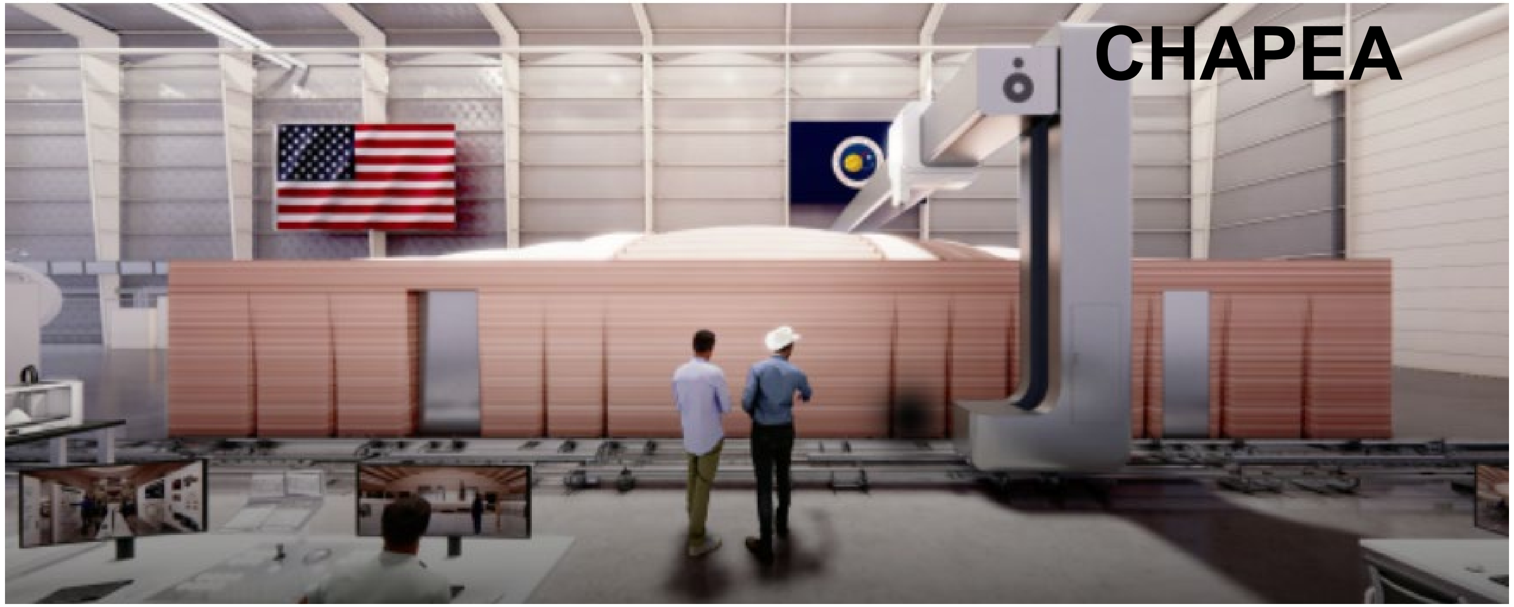
International Space Station → Gateway → Lunar Surface → Mars Transit

CURRENT STATE	EXPLORATION CLASS MISSION
• 180-day to 360 -day mission duration	• 650-day to > 900 -day mission duration
• Strong consumables resupply	• Zero consumables resupply
• Real-time communications	• No real-time communications
• Regular sample returns to Earth	• No sample returns to Earth
• Emergency evacuations possible	• No evacuations possible
• Relatively large internal volume	• (Likely) much smaller internal volume
• Limited onboard medical care (Earth -reliant)	• Expanded onboard medical care (crew/vehicle -reliant)

Tasks: Isolation, Confinement and Communications Delay Analogs

HERA

- Isolated, confined & controlled
- 45-day missions
- Variable crew autonomy
- Standard MCC-crew interactions



CHAPEA

- Isolated & confined
- 378-day missions
- High crew autonomy
- Minimal MCC-crew

Top Crew Health and Performance System Capability Gaps for Mars

Earth-Independent Human Operations

Computational Injury & Anthropometric Models

Mars Duration Food System

Exploration Exercise Countermeasures

Mars Duration Effects on Human Physiology

Understanding Individual Variability in Spaceflight

P.S.I.

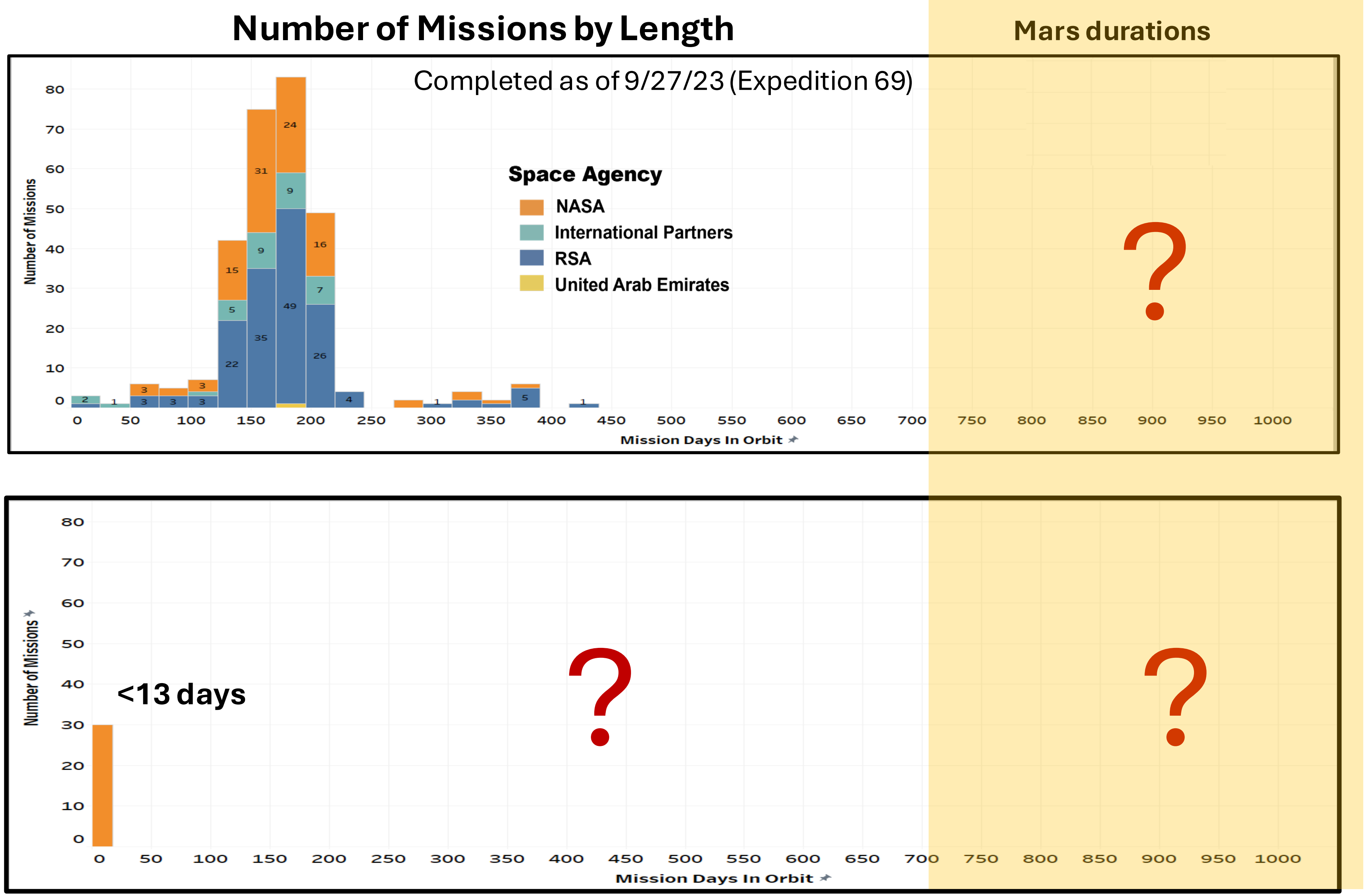
Risk Mitigations for Vehicle Atmospheres

Sensorimotor Countermeasures

Limited Extended-Duration Data Creates Large Unknowns

LEO Conditions
(ISS/MIR/Salyut)

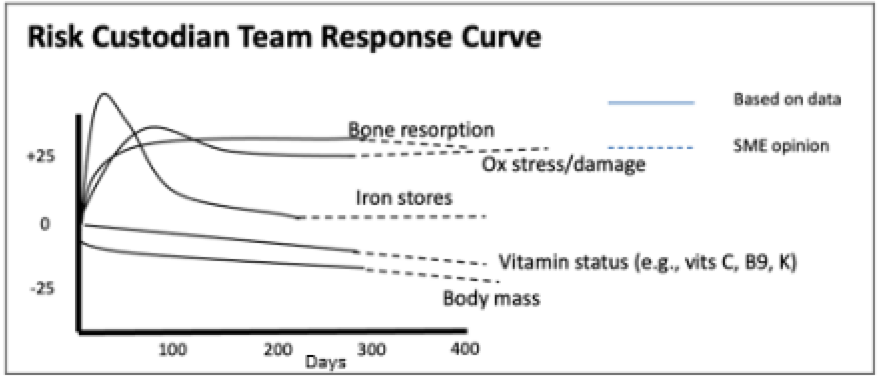
Deep Space/Lunar Conditions
(Apollo)



Time Course Spaceflight Changes Examples

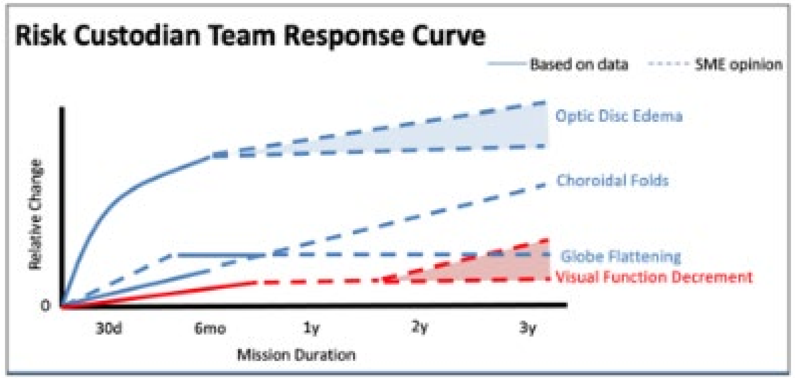
Appears to generally plateau by 6 months

Nutrition/Biochemistry



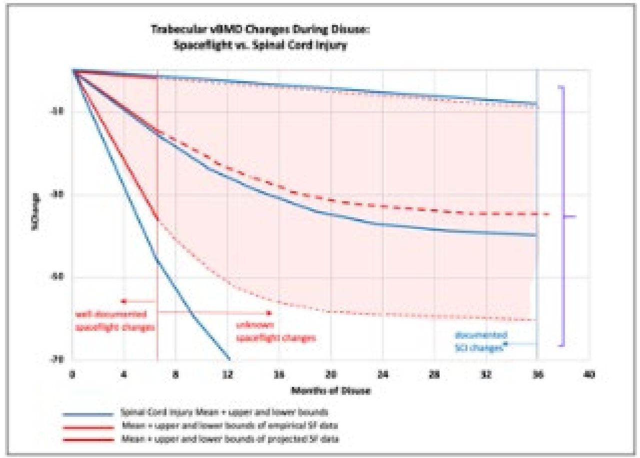
<u>Does not</u> appear to plateau by 6 months in some crewmembers

Spaceflight Associated Neuro-ocular Syndrome (SANS)

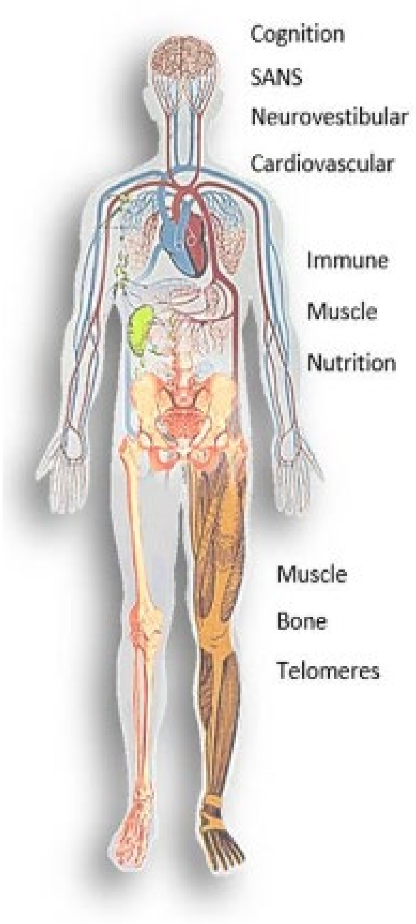


Unknown

Bone Quality



Complement of Integrated Protocols for Human Exploration Research



The CIPHER **integrated** protocol is composed of **14 multi-disciplinary, multi-national investigations** that have been integrated into a **single research complement** that addresses over **20 Human System Spaceflight Risks.**

Mars-forward use of ISS to measure the time course of **physiological and psychological adaptations** to spaceflight to reduce crew health & performance risks during multi-year deep space exploration missions.

Designed to be conducted on 30 crew members of varying mission durations, but categorized into three subject pools:

- **Short**: 30 to 105 days
- **Standard**: 106 to 239 days
- **Extended**: 240+ days

Top Crew Health and Performance System Capability Gaps for Mars

- Earth-Independent Human Operations
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- Mars Duration Effects on Human Physiology
- **Risk Mitigations for Vehicle Atmospheres**
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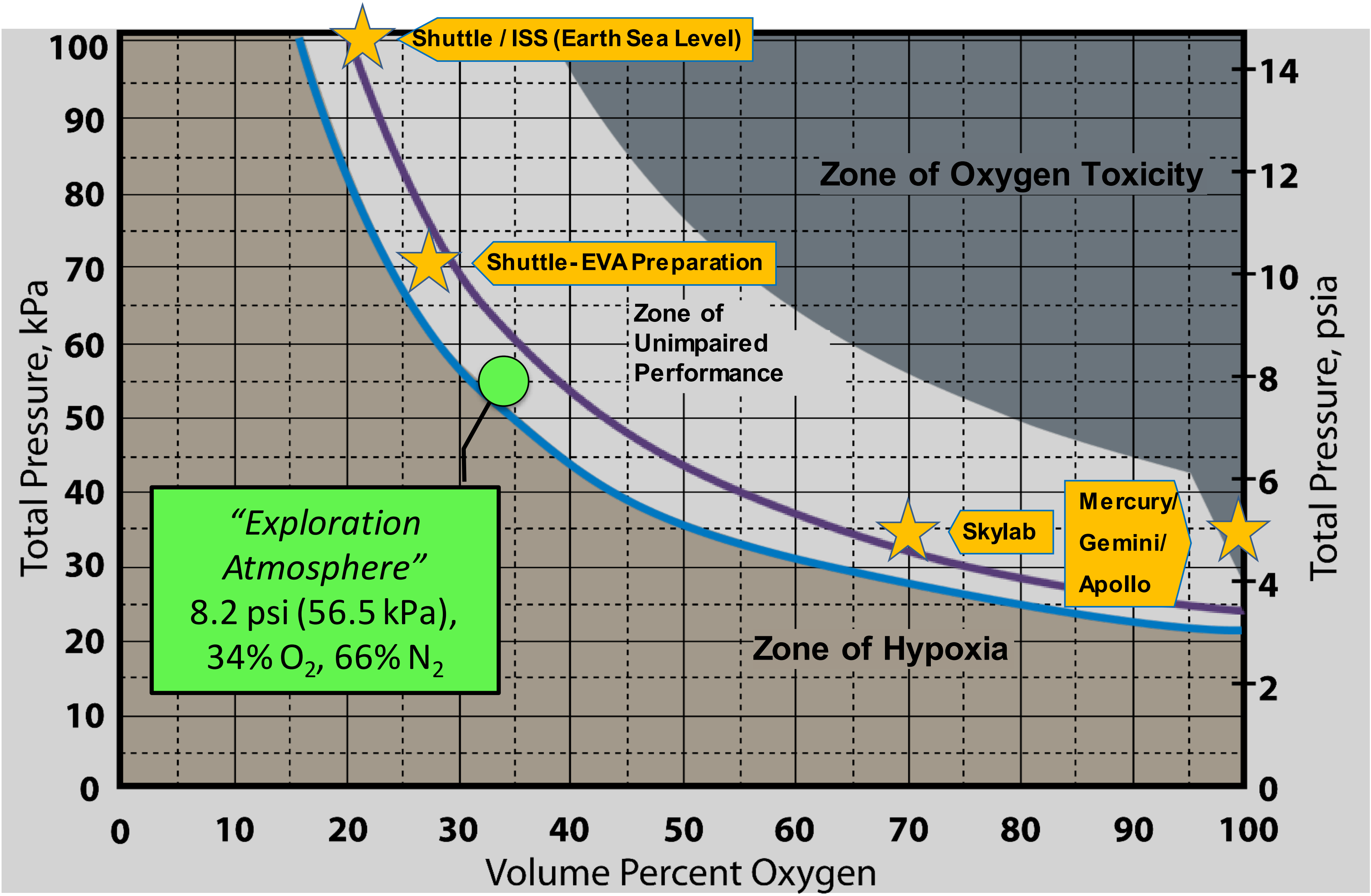
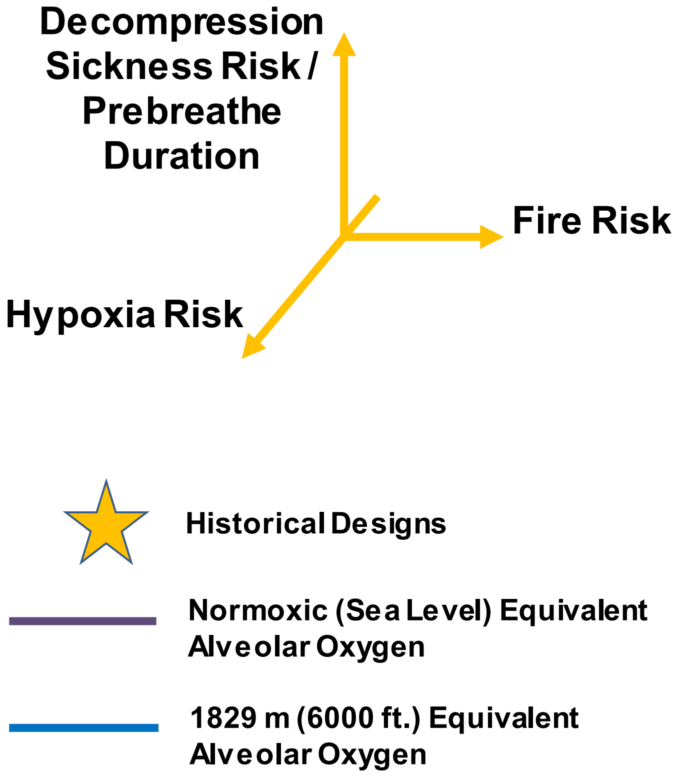
- Understanding Individual Variability in Spaceflight
- Sensorimotor Countermeasures

Spacecraft Atmospheres





For high-frequency EVA

NASA/TP-2010-216134: Recommendations for Exploration Spacecraft Atmospheres - The Final report of the NASA Exploration Atmospheres Working Group. D. L. Henninger, Chair

Rationale for Exploration Atmosphere

- Multidisciplinary Working Group recommendation to adopt 8.2 psia / 34% O2 as a capability for future missions <u>involving high frequency EVA</u>[1]
- Provided recommendations for Human research studies, materials flammability, life support, EVA systems

Saturation Atmosphere	Microgravity Prebreathe* (h:mm)	<u>Estimated</u> Planetary Prebreathe*
14.7 psi, 21% O2	4:00	6:30-7:00 [2]
10.2 psi, 26.5% O2	0:40	3:00-3:30 [3]
8.2 psi, 34% O2	**0:00-0:15**	**0:20** [4,5]
5.0 psi, 100% O2 (Apollo, Gemini)	0:00	0:00

***Assume 6hr EVA @ 4.3 psia**

Unvalidated (i.e., not yet available for flight use)

Validated via Ground Testing

[1] NASA/TP-2010-216134/JSC 63309, Recommendations for Exploration Spacecraft Atmospheres - The Final report of the NASA Exploration Atmospheres Working Group

[2] Abercromby et al. *"Suited Ground Vacuum Chamber Testing Decompression Sickness Tiger Team Report"*, 2018 NASA Technical Report

[3] Abercromby, et al. *"Using the Shuttle Staged Prebreathe Atmosphere and Variable Pressure Spacesuits for Exploration Extravehicular Activity"*, 2018 AsMA.

[4] Abercromby et al. *"Modeling Oxygen Prebreathe Protocols for Exploration EVA Using Variable Pressure Suits"*, 2017 AsMA.

[5] Abercromby et al. "Modeling a 15-min extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5 kPa/34% O2)", Acta Astronautica, 109 (2015), pp.76-87.

Tasks: Exploration Atmosphere Testing in JSC's 20 ft Chamber

Top Crew Health and Performance System Capability Gaps for Mars

Earth-Independent Human Operations

Mars Duration Food System

Mars Duration Effects on Human Physiology

Risk Mitigations for Vehicle Atmospheres

P.S.I.

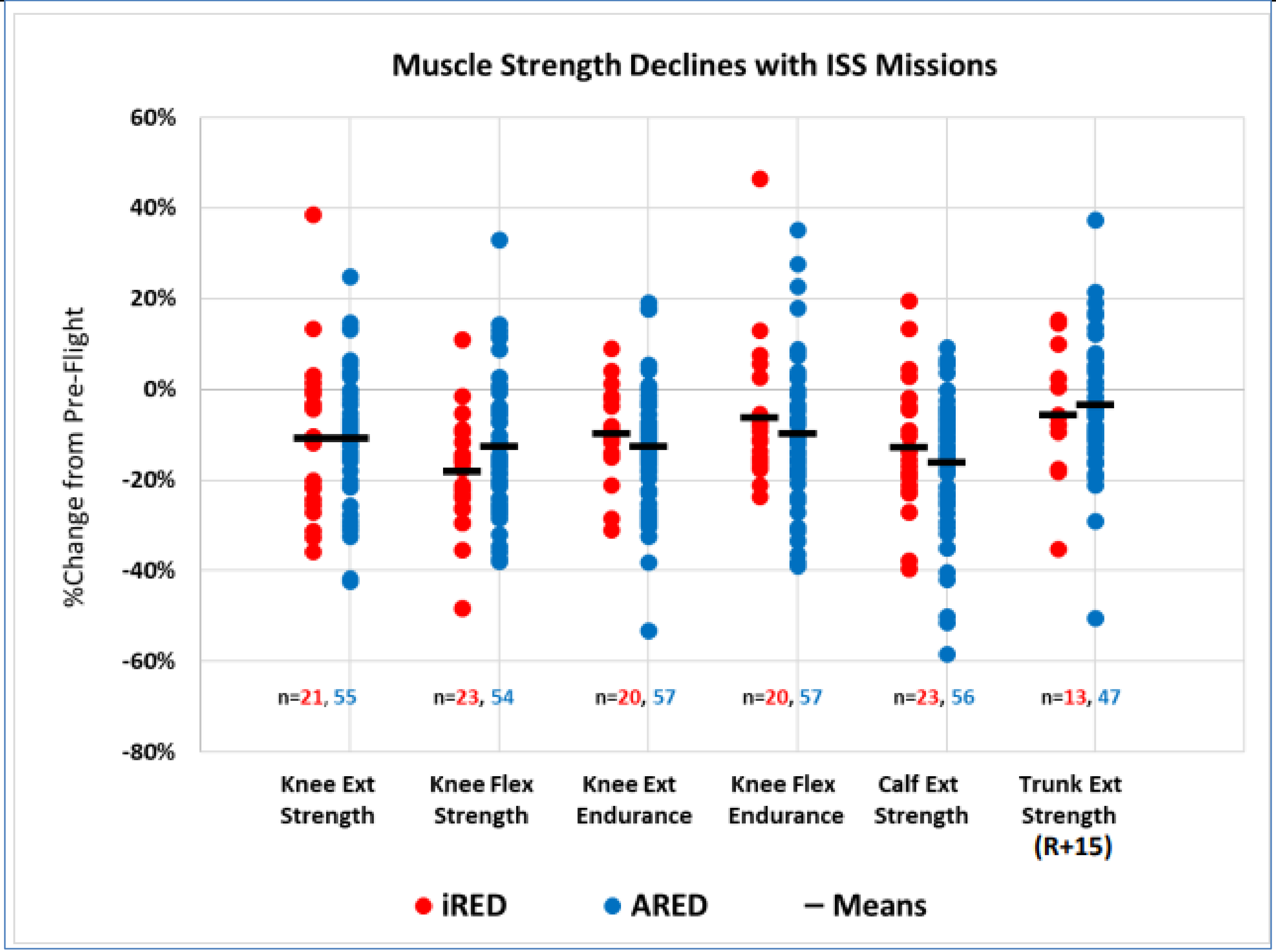
Computational Injury & Anthropometric Models

Exploration Exercise Countermeasures

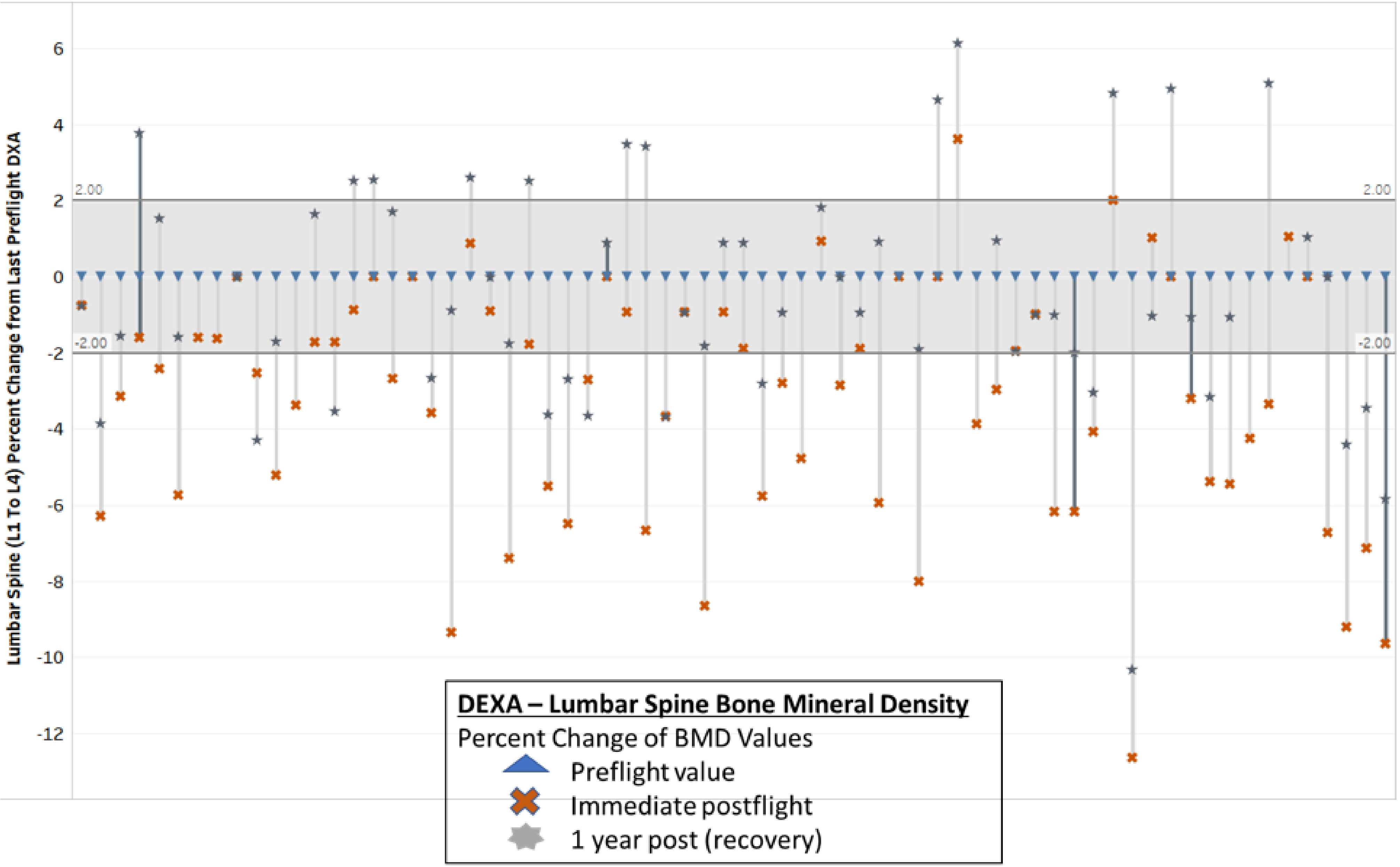
Understanding Individual Variability in Spaceflight

Sensorimotor Countermeasures

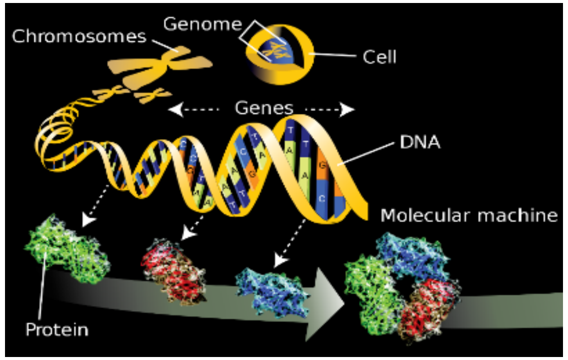
Example of Individual Variability in Spaceflight Physiology: Muscle



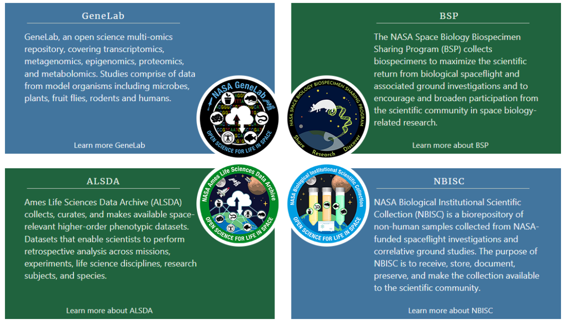
Duration vs. Individual Variability: Pre/Post Bone DXA measurements



Tasks: Gathering and Making Datasets More Accessible for Analysis



NASA Omics Data Archive - https://www.nasa.gov/mission/station/research-explorer/investigation/?#id=8275
ISS flight study



NASA's Open Science Data Repository (OSDR) - https://osdr.nasa.gov/bio/

- Genelab
- Biospecimen Sharing Program (BSP)
- Ames Life Sciences Data Archive (ALSDA)
- (NASA) Biological Institutional Scientific Collection (NBISC)

NASA's Life Science Portal (NLSP) - https://nlsp.nasa.gov/explore/lsdahome

- Life Science Data Archive
- Lifetime Surveillance of Astronaut Health

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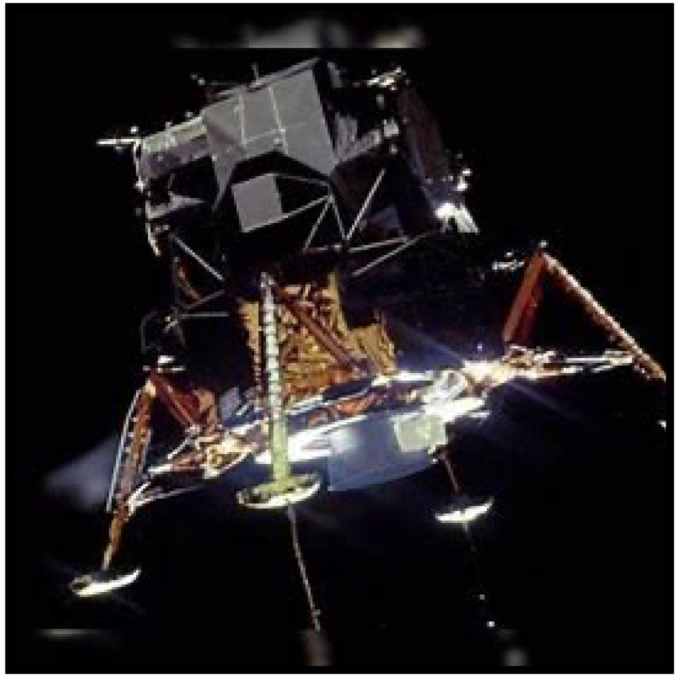
State-of-the-Art Landings on Earth After Six Months in Low Earth Orbit

Mars Landing

Sensorimotor Capabilities Needed for Critical Activities

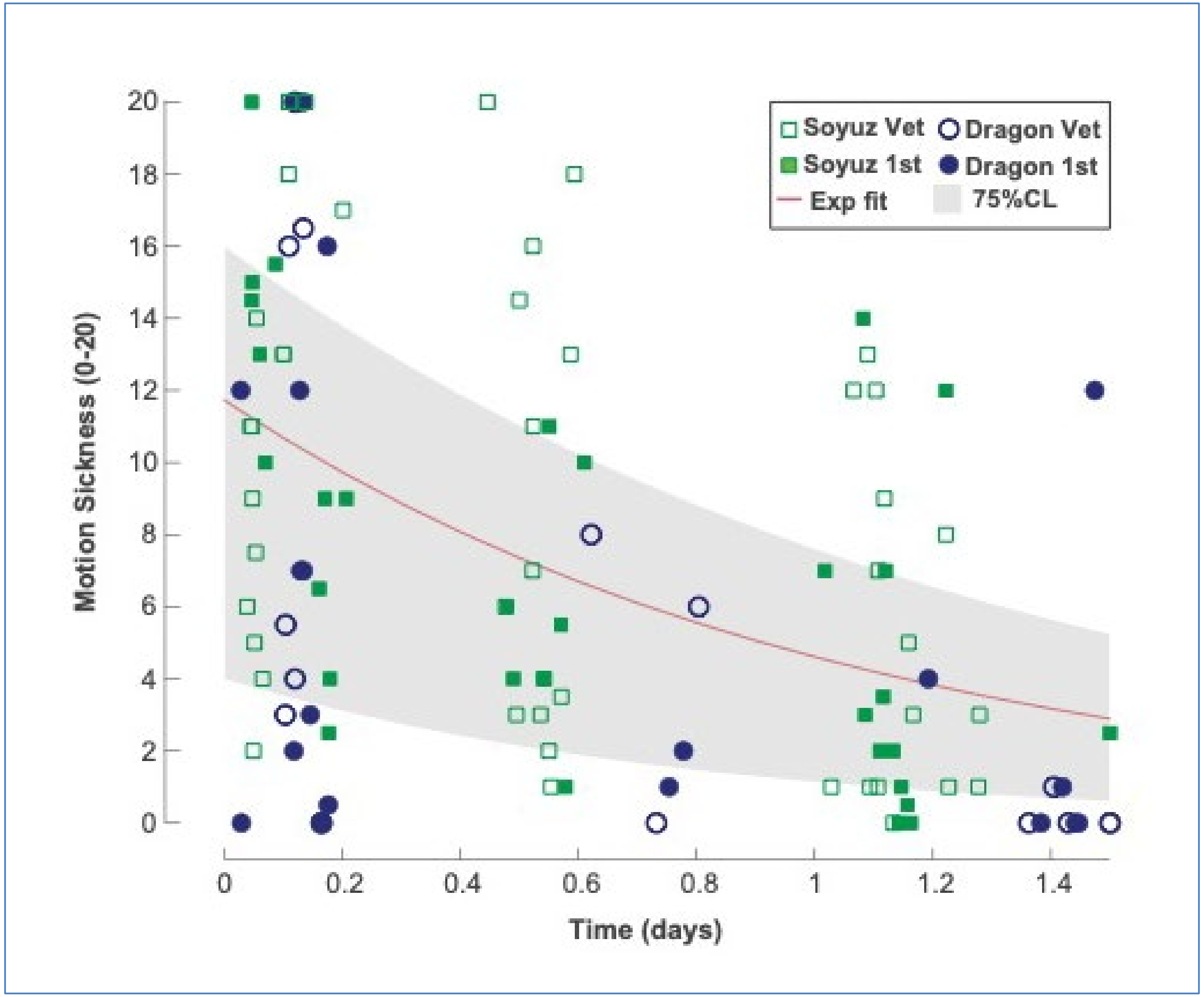


Manual Control

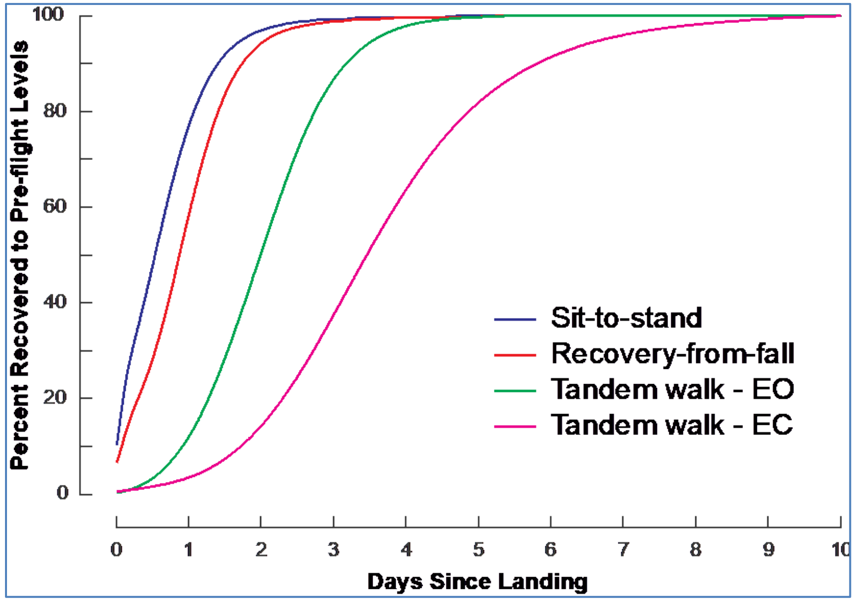
Early EVA

Crew Egress

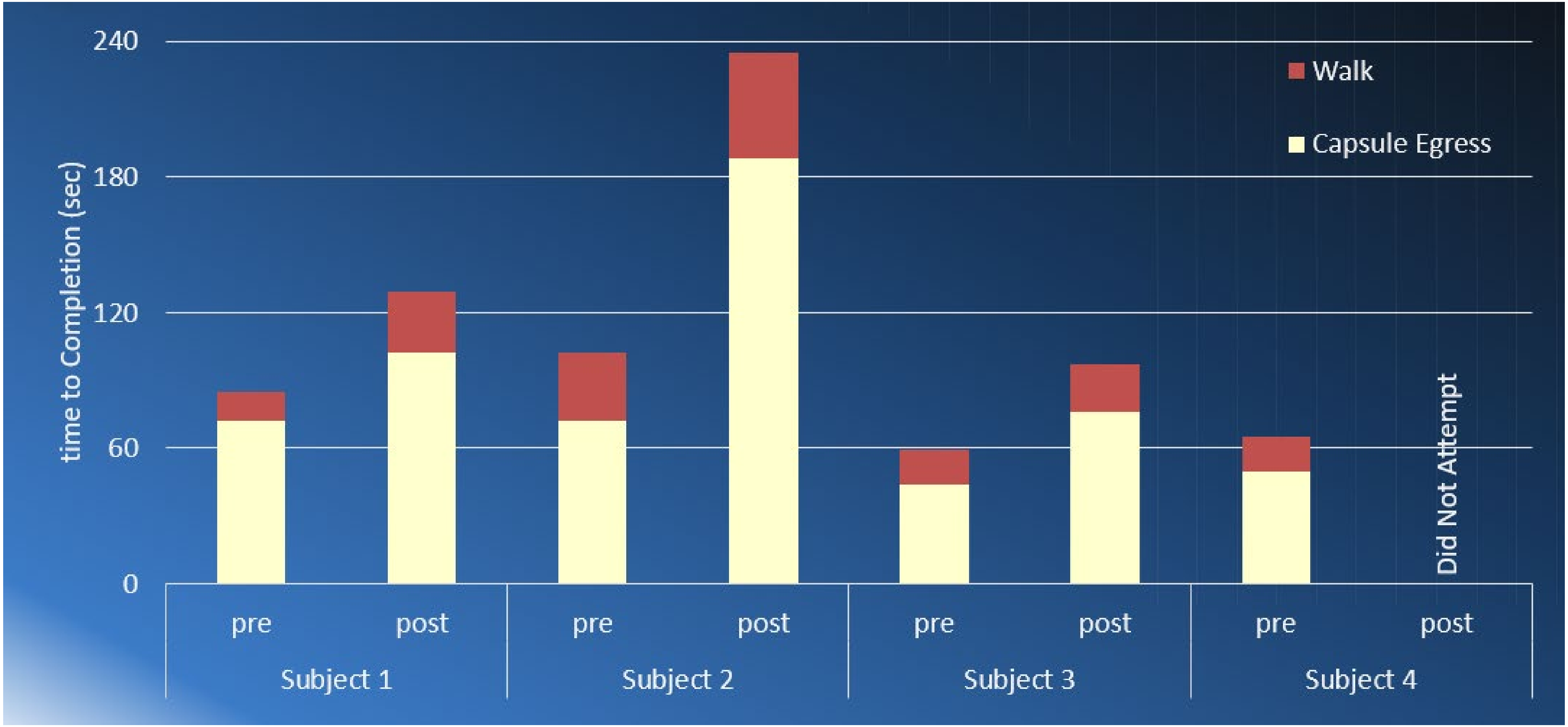
Sensorimotor Re-Entry Recovery



- Symptom severity highly variable across crewmembers
- Head movement wrt gravity are more provocative
- Recovery to baseline performance varies by task

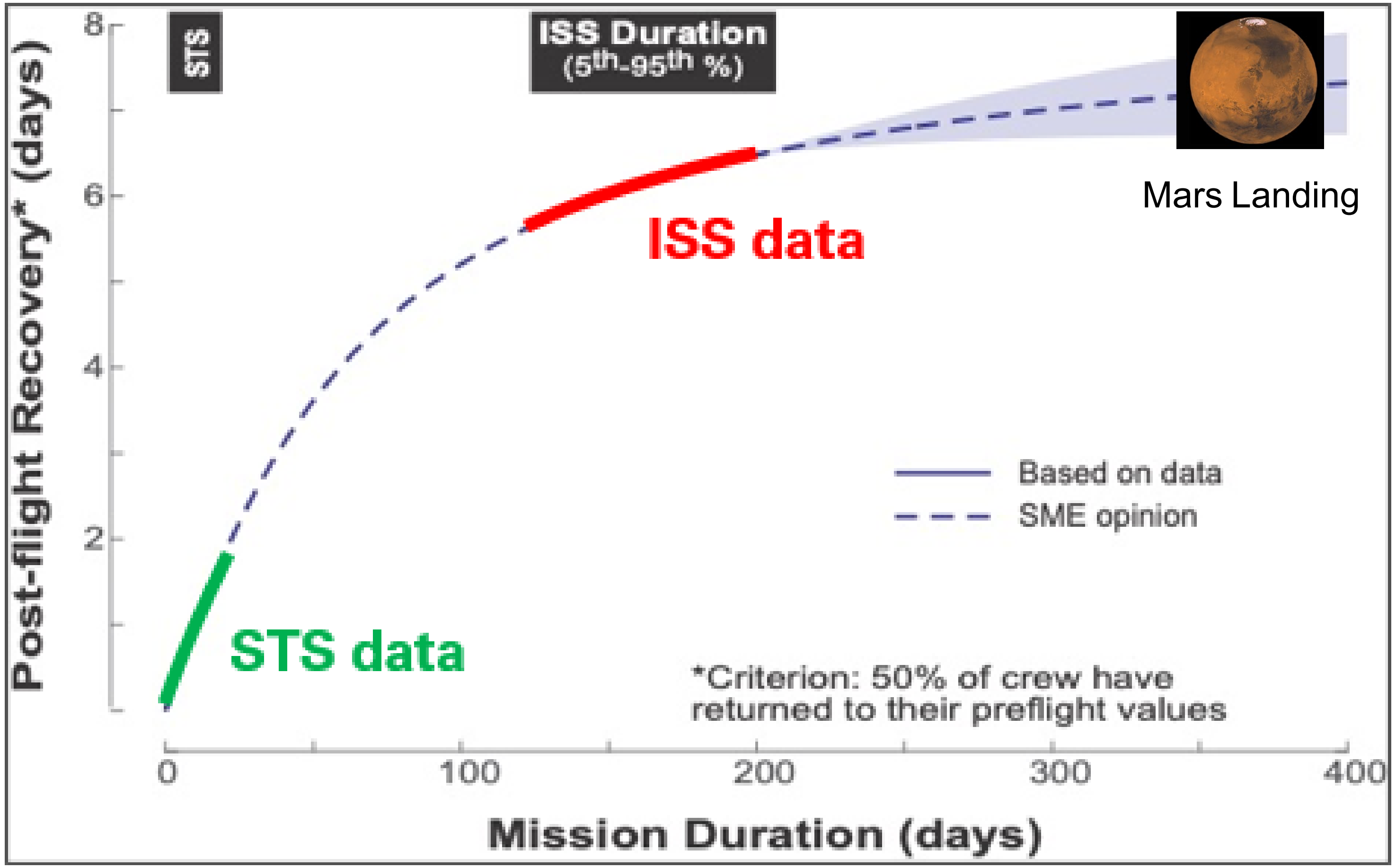


Mock-up Capsule Egress Results

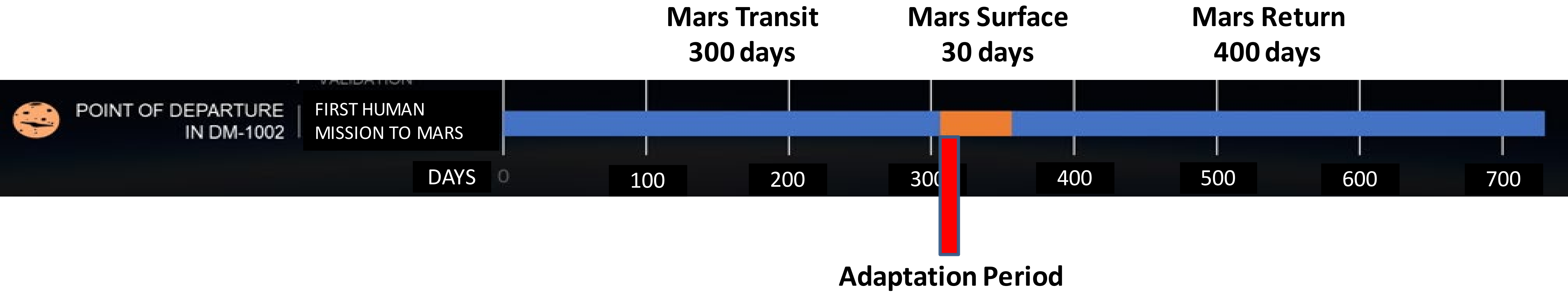


Postflight Recovery Curves for Sensorimotor Adaptation

Field Test was performed in the medical tents or rally airports as soon as possible after landings.



Example of a Mars Architecture Team timeline



Mars Architecture Team (MAT) is protecting **3-7 days** for Sensorimotor adaptation after landing on Mars for nominal EVAs

Depending on the Mars surface stay duration, that could represent a significant percentage of the planetary science timeline.

Task: Sensorimotor Countermeasure Development and Testing

KRAKEN Disorientation Device at NAMRU-D

Kraken is a state-of-the-art Navy motion simulator that can be utilized to mitigate emerging Lunar landing HLS risks and test sensorimotor countermeasures for landing, egress and early EVA's.

What are we doing to protect crews from radiation?
ALARA – As Low as Reasonably Achievable (GCR and SPEs)

Institutionalizing knowledge: NASA-STD-3001 standards and recent updates

1. **Galactic Cosmic Ray (GCR)** Shielding
2. Personal radiation exposure monitoring
3. Lifetime space radiation exposure limits (600mSv)
4. Design standards for **Solar Particle Events (SPE)** impacts and "storm shelters"
5. Real-Time Radiation Monitoring for Protection

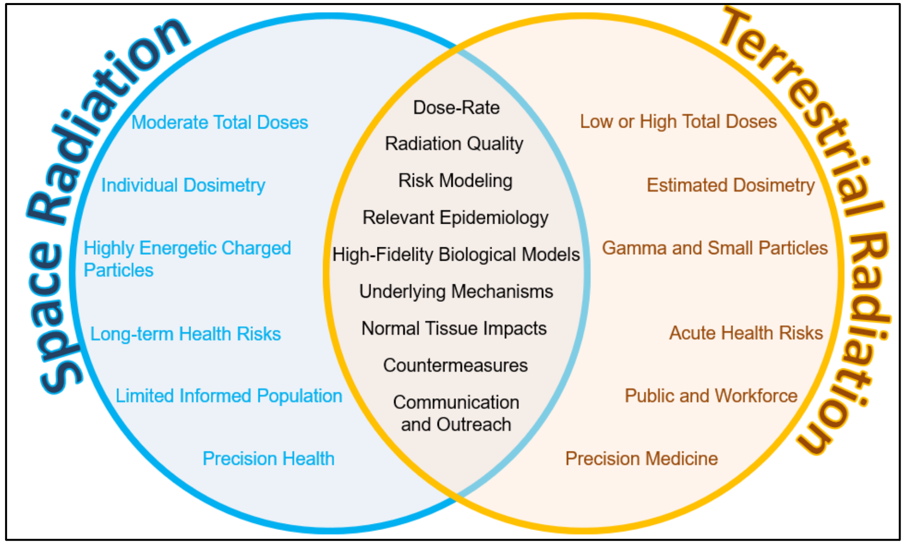
Continue mitigation strategies: Space Radiation Research

1. Characterize space environment on biology with GCR simulator
    - Dose Quality (Mixed Field GCR vs. Gamma)
    - Dose Rate (Dose provided over weeks vs. single exposure)
    - GCR Simulation in use since 2018 – first suite of studies starting to report results.
2. Leverages significant investment in **terrestrial radiation research** for **prevention, detection, treatment and personalized assessments**
3. Tools for **informed consent** for crews and agency decision makers
4. Improve SPE forecasting tools and technologies to minimize crew exposure levels

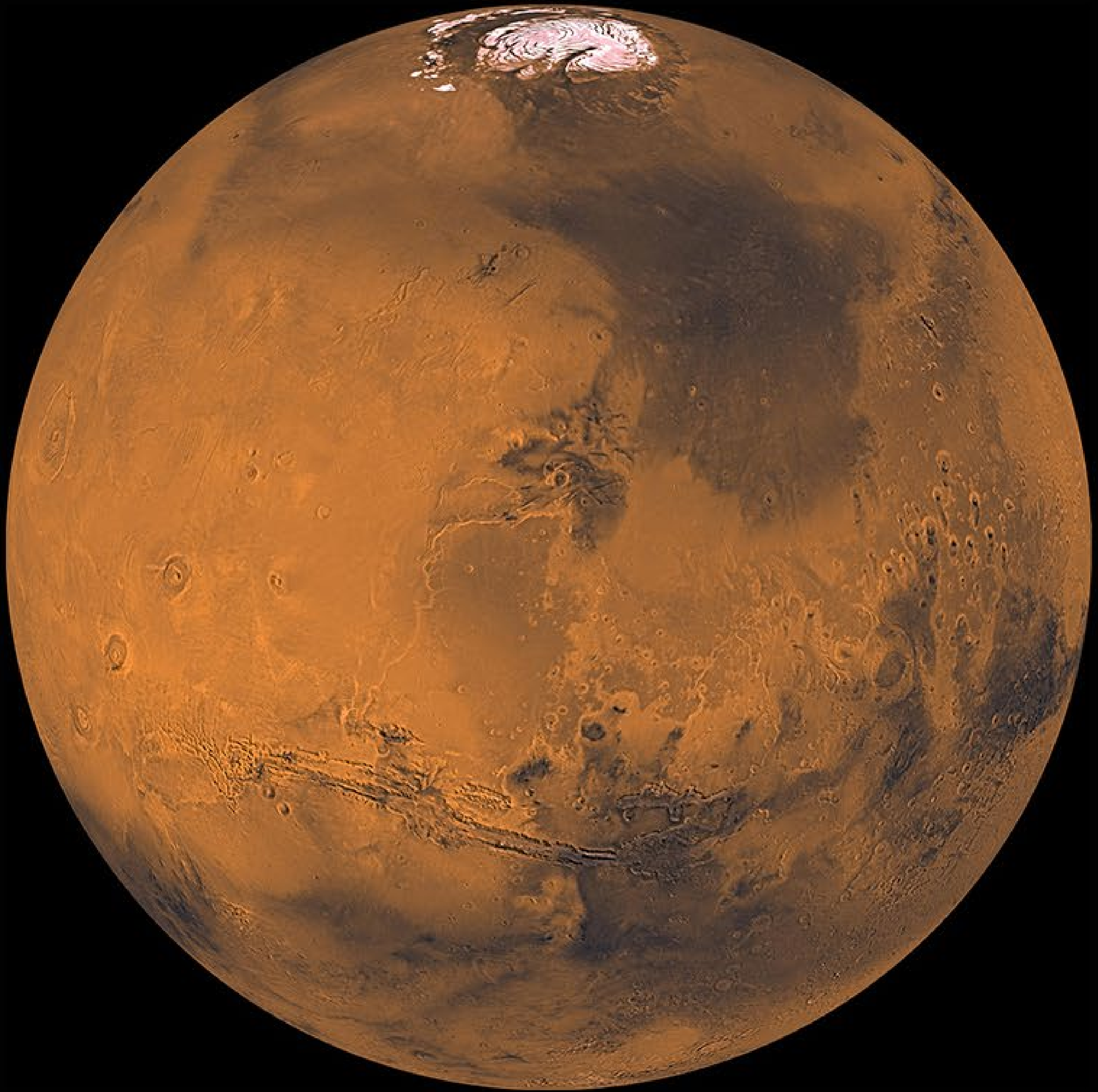
Providing recommendations to Agency: Mission Architecture Planning

1. Fly during Solar Maximum
2. Fly shorter Missions

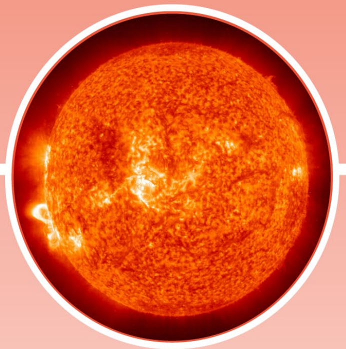
NASA's Space Radiation Laboratory (NSRL) provides the highest fidelity simulation of Galactic Cosmic Radiation (GCR) on Earth



Research on Mars



Artemis vs. Mars: 5 Hazards



Space Radiation

Longer exposure to deep space ionizing radiation.

Isolation & Confinement

Longer missions with same crew in same transit vehicle; majority of missions will be without views of the Earth

Distance from Earth

No resupply, multi-month/year return to Earth, longer communication delays, more crew and vehicle autonomy

Lack of Gravity

Longer periods in microgravity; partial gravity different; "heavier" EVA suit.

Hostile/Closed Environment

Different atmospheric pressure/partial pressure of oxygen (TBD), different microbial environment, limited food system, different exercise capability; Martian dust exposure.

Synergistic interaction of all five hazards acting on human body simultaneously

HRP Mars Goal & Objectives

Enable crews to thrive during Mars missions, protect their long-term health, and enable human exploration beyond Mars.

1. **Exploration Medical Operations**
   Validate Earth-independent crew health & performance systems and operations.
2. **Integrated Human System Performance**
   Validate countermeasures and characterize impacts to overall crew health & performance.
3. **Living Environment**
   Validate the interaction of exploration habitation systems, spaceflight hazards, and effects on crew health & performance.
4. **Special Task-Related Issues**
   Validate operational implementation of critical tasks, protocols, procedures, and human factors for adequate crew health & performance.
5. **Extended Mission Durations**
   Validate human system risk mitigation strategies in Mars-class duration missions and systems.

HRP & Planetary Science Collaborations

WHY:

NASA's Science Mission Directorate (SMD) is planning science objectives and related crew tasks/activities for Artemis and Mars missions. HRP is planning research tasks to enable human health and performance on Artemis and Mars missions. Collaboration allows for 1) potentially improved SMD crew tasks and mission timelines, and 2) more refined/accurate HRP research tasks.

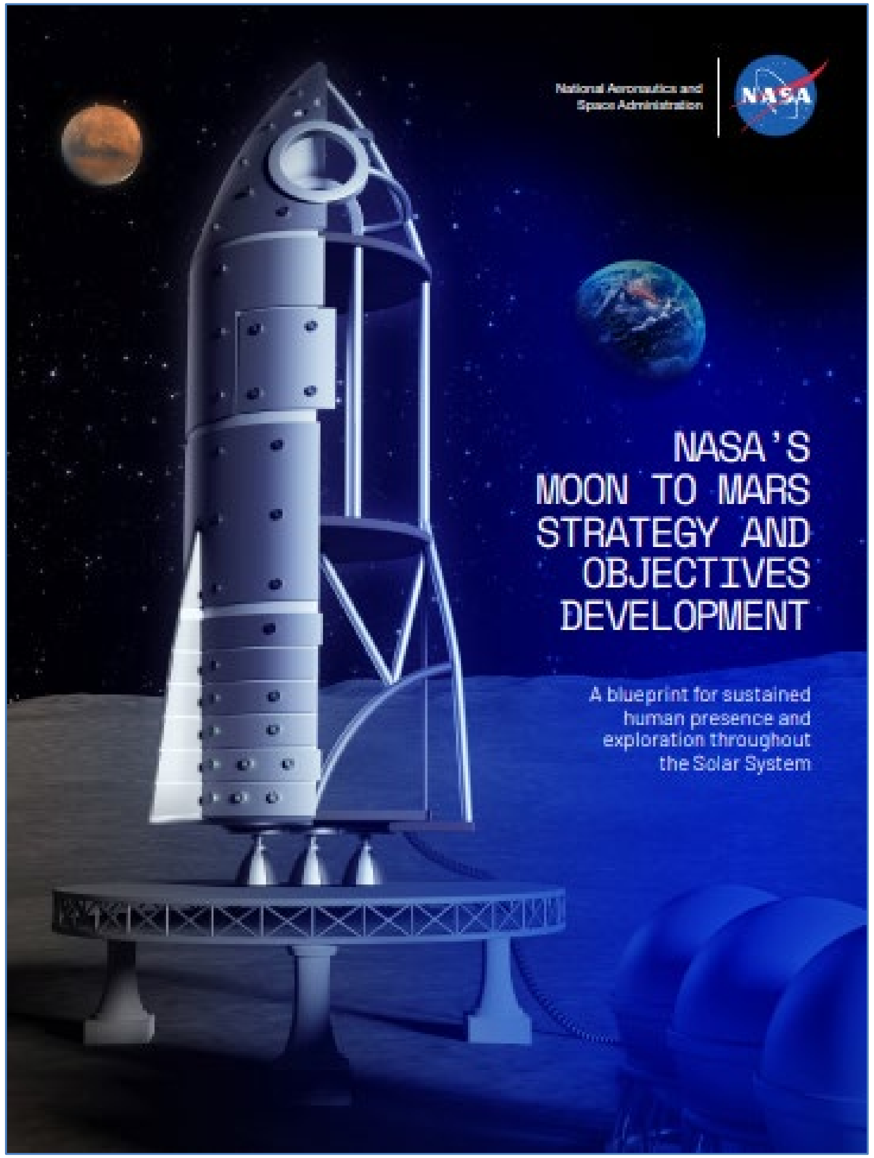
HOW:

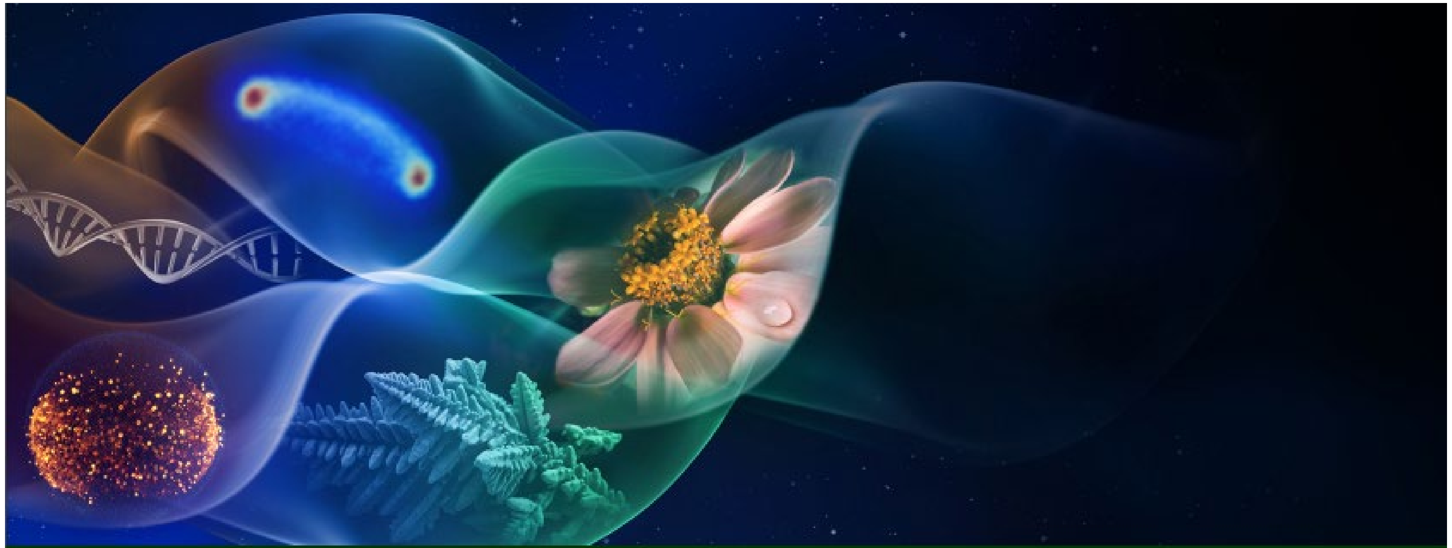
1. SMD is presenting to HRP this spring to brief EVA planned activities and sampling strategy.
2. Deeper dive/targeted presentations by SMD to HRP's Scientists every quarter.
3. HRP 2025 Investigator's Workshop proposed plenary by SMD
4. Cross-participation or observation in each other's analog missions (where applicable)

WHAT:

1. HRP refined research tasks to enable SMD science on Artemis & Mars missions
2. Ground analogs collaboration ideas

M2M strategy: HRP-Specific Objectives





Human and Biological Science (HBS)

Goal: Advance understanding of how biology responds to the environments of the Moon, Mars, and deep space to advance fundamental knowledge, to support safe, productive human space missions, and to reduce risks for future exploration.

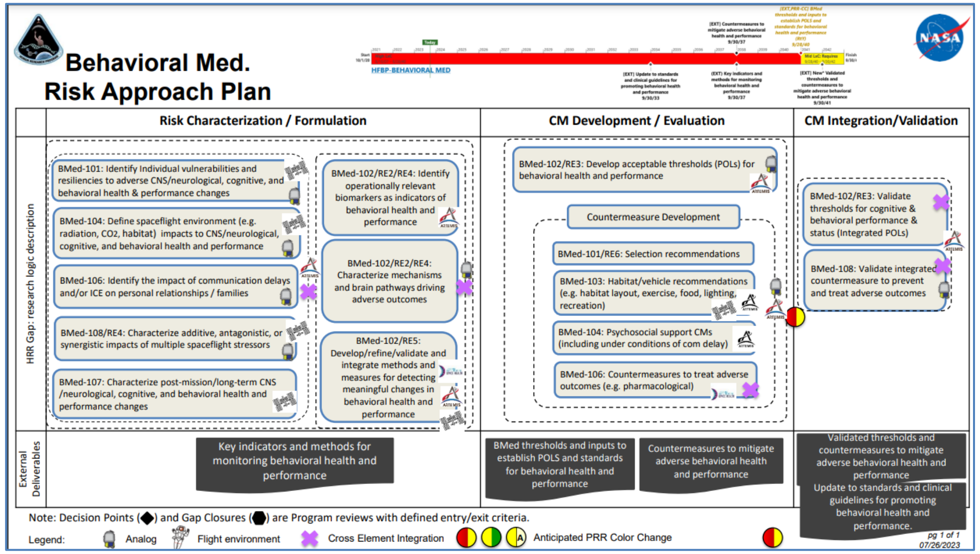
HBS-1^LM^:	Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants.
HBS-2^LM^:	Evaluate and validate progressively Earth-independent crew health and performance systems and operations with mission durations representative of Mars-class missions.
HBS-3^LM^:	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.

https://www.nasa.gov/sites/default/files/atoms/files/m2m_strategy_and_objectives_development.pdf

HRP M2M Iterative Strategy:

Enable and Utilize Artemis Missions as a Mars Testbed to Characterize and Mitigate Human System Risks

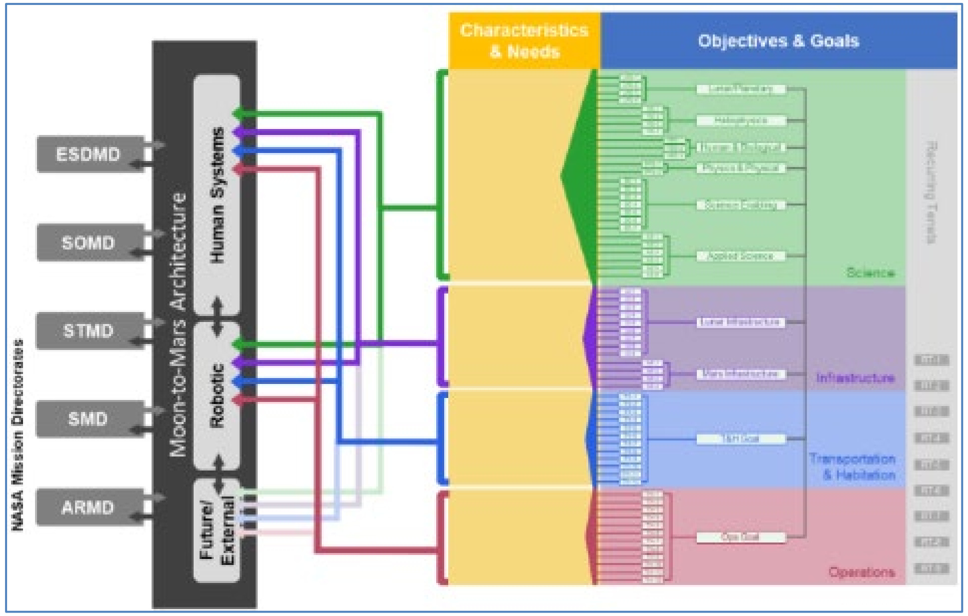
HRP Risk Approach Plans (RAPs)



Decompose into RAPs

Inform Architecture

M2M Architecture Definition Document



HRP Risk Approach Plans (RAPs) serve as both an ADD decomposition and an input

Moon2Mars Architecture Objectives for Crew Health and Performance

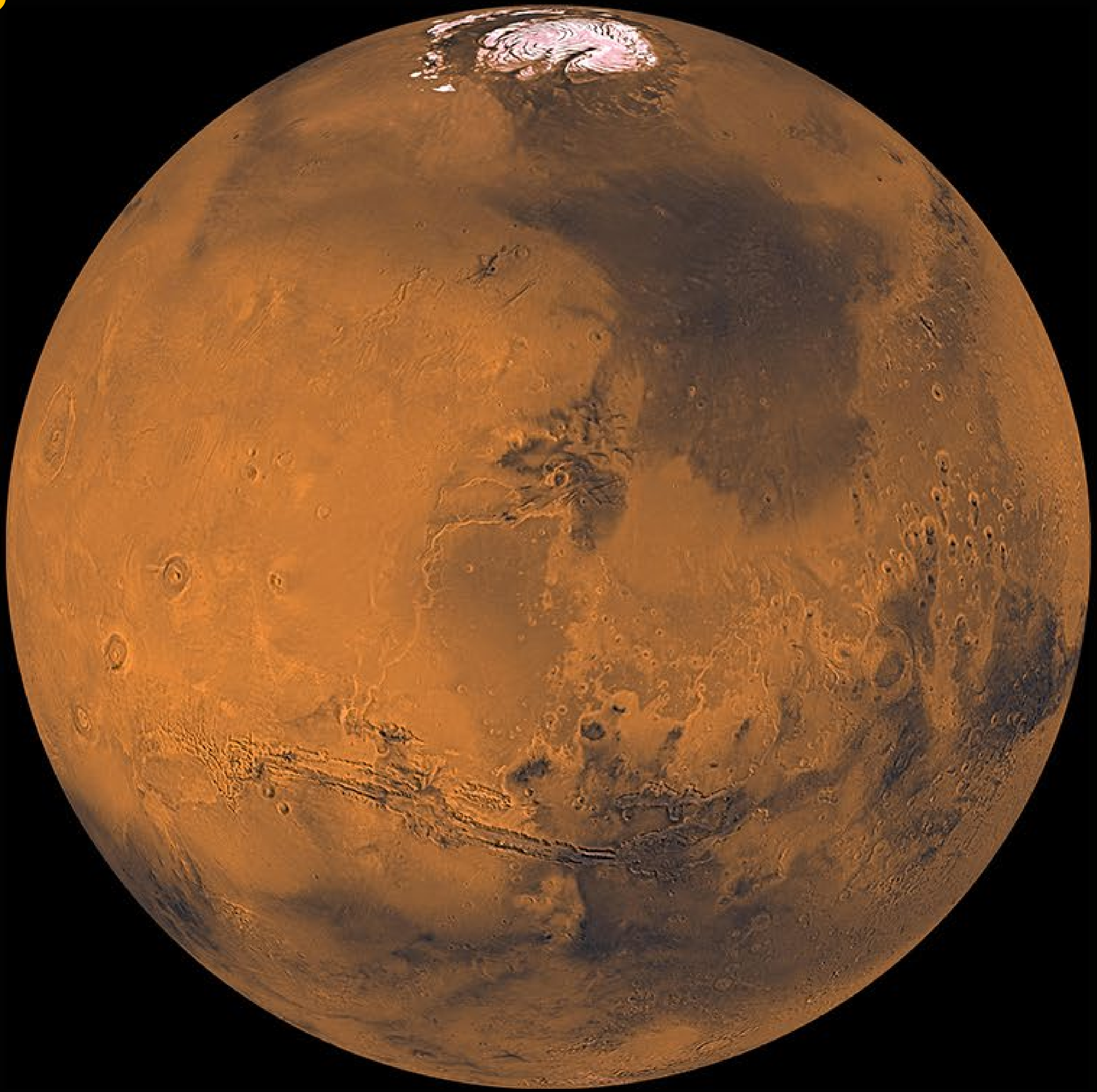
OBJ	DESCRIPTION
OP-1L	Conduct human research and technology demonstrations on the surface of Earth, low-Earth orbit platforms, cislunar platforms, and on the surface of the Moon, to evaluate the effects of extended mission durations on the performance of crew and systems, reduce risk, and shorten the timeframe for system testing and readiness prior to the initial human Mars exploration campaign.
OP-6L	Evaluate, understand, and mitigate the impacts on crew health and performance of a long deep space orbital mission, followed by partial gravity surface operations on the Moon.
OP-7LM	Validate readiness of systems and operations to support crew health and performance for the initial human Mars exploration campaign.
HBS-01LM	Understand the effects of short- and long-duration exposure to the environments of the Moon, Mars, and deep space on biological systems and health, using humans, model organisms, systems of human physiology, and plants.
HBS-02LM	Evaluate and validate progressively Earth-independent crew health & performance systems and operations with mission durations representative of Mars-class missions.
HBS-03LM	Characterize and evaluate how the interaction of exploration systems and the deep space environment affect human health, performance, and space human factors to inform future exploration-class missions.

Recommended reading and additional resources

- **Moon2Mars Human Health white paper**
  - https://www.nasa.gov/wp-content/uploads/2024/01/human-health-and-performance.pdf
- **NASA Office of the Chief Health and Medical Officer (OCHMO) Technical Briefs**
  - https://www.nasa.gov/ochmo/health-operations-and-oversight/hsa-standards/ochmo-technical-briefs/
- **Human research roadmap websites (evidence, risks, gaps, risk approach plans)**
  - https://humanresearchroadmap.nasa.gov/
- **HRP Evidence reports**
  - https://humanresearchroadmap.nasa.gov/Evidence/
- **Annual Human Research Program Investigator Workshop**
  - https://www.nasa.gov/hrp-iws-2024/

- **My email**
  - david.k.baumann@nasa.gov

Questions?



BACKUP:
List of Lunar and Mars Research Gaps by Risk

RAP		GAP Description	Artemis Relevance
Medical	Medical-101	Characterize Conditions and define end states; IMPACT Medical Condition List can be used to scope Artemis medical capabilities for medical system design	Enabling
Medical	Medical-301	Highest benefit on the End States per unit "cost"; A prioritized capability list can be used by future exploration programs for medical system design	Enabling
Medical	Medical-501	Translate medical capabilities into engineering language to enable a program to action recommendations using systems engineering. Enabling: ExMC-developed medical system models can be used by exploration programs as a Foundation from which they can tailor their individual medical systems. Utilization: utilize Artemis missions to test and validate exploration-forward med systems	Enabling/Utilization
Medical	Medical-701	How do we increase inflight capabilities or find new capabilities to maximize the impact on the aggregate medical risk? How can we lessen the "cost" of a medical capability on vehicle/mission resources?	Utilization
Pharm	Pharm-101	Perform market analysis of packaging/storage options	Utilization
Pharm	Pharm-201	Exploration Candidate Formulary (ECF) v1.0 - 4.0	Enabling
Pharm	Pharm-301	Define a process for assigning medications to colors on the stoplight chart. ECF 1.0 Stoplight-Baseline ECF v1.0 - 4.0 Stoplight Chart	Enabling
Pharm	Pharm-401	Further study the safety and effectiveness of medications determined to be yellow on the most current version of the Stoplight Chart (concurrent with gaps Pharm-201 and Pharm-301). Also consider interaction with packaging/storage from gap Pharm-101.	Utilization

RAP		GAP Description	Artemis Relevance
Bmed	Bmed-101a	Identify individual vulnerabilities and resiliencies to adverse CNS/neurological, cognitive, and behavioral health & performance changes	Utilization
Bmed	Bmed-101b/RE6	Selection recommendations	Utilization
Bmed	Bmed-102a/RE2/RE4	Identify operationally relevant biomarkers as indicators of behavioral health and performance	Utilization
Bmed	BMed-102b/RE2/RE4	Characterize mechanisms and brain pathways driving adverse outcomes	Utilization
Bmed	Bmed-102c/RE5	Develop/refine/validate and integrate methods and measures for detecting meaningful changes in behavioral health and performance	Utilization
Bmed	Bmed-102d/RE3	Develop acceptable thresholds (POLs) for behavioral health and performance	Utilization
Bmed	Bmed-102e/RE3	Validate thresholds for cognitive & behavioral performance & status (Integrated POLs)	Utilization
Bmed	Bmed-103	Habitat/vehicle recommendations (e.g. habitat layout, exercise, food, lighting, recreation)	Enabling/Utilization

RAP		GAP Description	Artemis Relevance
Bmed	Bmed-104a	Define spaceflight environment (e.g. radiation, CO2, habitat) impacts to CNS/neurological, cognitive, and behavioral health and performance	Utilization
Bmed	Bmed-104b	Psychosocial support CMs (including under conditions of com delay)	Enabling/Utilization
Bmed	Bmed-106a	Identify the impact of communication delays and/or ICE on personal relationships / families	Utilization
Bmed	Bmed-106b	Countermeasures to treat adverse outcomes (e.g. pharmacological)	Utilization
Bmed	Bmed-106c	Validate integrated countermeasure to prevent and treat adverse outcomes	Utilization
Bmed	Bmed-107	Characterize post-mission/long-term CNS /neurological, cognitive, and behavioral health and performance changes	Utilization
Bmed	Bmed-108/RE4	Characterize additive, antagonistic, or synergistic impacts of multiple spaceflight stressors	Utilization

RAP		GAP Description	Artemis Relevance
Dynamic Loads	DL-101a	Characterize risk of injury associated with crewed vehicle landings and how it relates to the desired acceptable risk	Enabling/Utilization
Dynamic Loads	DL-101b	Characterize individual factors (e.g. deconditioning, sex differences) and contributions to increased risk of injury	Enabling/Utilization
Dynamic Loads	DL-401	Determine extent to which multiple spaceflight hazards may interact to decrease injury tolerance for off-nominal dynamic landing loads	Enabling/Utilization
Dynamic Loads	DL-201a	Develop Injury Assessment Reference Values to help characterize specific risk of injury to the crew	Enabling/Utilization
Dynamic Loads	DL-201b	Using standard approaches, develop and test analytic models to allow for specific risk injury predictions	Enabling/Utilization
Dynamic Loads	DL-301	Validate standardized approach for vehicle instrumentation, biodynamic data collection, and predictive analytic modeling that allows for specific injury risk prediction by mission phase, crew functionality post-landing, and vehicle design	Enabling/Utilization

RAP		GAP Description	Artemis Relevance
HSIA	HSIA-101	Characterize risk and define solution space formulation (simulation, scenarios, architecture, integration)	Enabling
HSIA	HSIA-201	Cross-cutting Human Factors tools, metrics, and solutions. Requirement for measuring consistency and countermeasures for working with diverse designs	Utilization
HSIA	HSIA-301	Develop and test complex procedure execution and oversight CMs	Enabling
HSIA	HSIA-401	Develop and test data and information management	Enabling
HSIA	HSIA-501	Develop and test CMs for assisted troubleshooting and problem solving, response decision	Utilization
HSIA	HSIA-601	Develop and test CMs for resource management	Utilization
HSIA	HSIA-701a	Flight test of integrated HSIA suite of CMs	Enabling
HSIA	HSIA-701b	Updates to system requirements, training, and requirements for autonomous operations	Enabling

RAP		GAP Description	Artemis Relevance
		misalignment, and associated impacts.	
Sleep	Sleep-102b	Evaluate individualized fatigue models to help inform scheduling	Enabling/Utilization
Sleep	Sleep-102c	Update habitability standards (lighting, temp, noise, air quality, privacy, caffeine) per DRM.	Enabling/Utilization
Sleep	Sleep-102d	Evaluate non-pharmacological treatment countermeasures (CBT, brain stimulation) relative to spaceflight	Enabling/Utilization
Sleep	Sleep-102f	Ground validation of CMs and models in Mars Sol.	Utilization
Sleep	Sleep-102e	Test and validate combined countermeasures and scheduling models inflight	Enabling

RAP		GAP Description	Artemis Relevance
Team	Team-102a	Measures to predict team performance and functioning	Utilization
Team	Team-102b	Establish team functioning and performance thresholds	Enabling
Team	Team-102c	Develop less obtrusive measures for monitoring and CM assessment	Utilization
Team	Team-103a	Develop and validate dynamic team composition algorithm and tool	Enabling/Utilization
Team	Team-103b	Validate team CM suite for composition, training, and support for multiple distributed teams	Utilization
Team	Team-104a	Identify countermeasures needed to support exploration and crews (e.g. team training methods)	Utilization
Team	Team-104b	Develop team CMs for exploration and integrated crews	Utilization
Team	Team-104c	Validate team CM suite for composition, training, and support for multiple distributed teams	Utilization
Team	Team-105a	Develop guidelines to support multiple, distributed teams	Utilization
Team	Team-105b	Validate team CM suite for composition, training, and support for multiple distributed teams	Utilization
Team	Team-106	Determine contributors to team outcomes	Utilization

RAP		GAP Description	Artemis Relevance
Bone	Bone-101	Characterize skeletal changes on bone mass (Bone Density) and bone structure (Bone Quality) of astronauts.	Enabling/Utilization
Bone	Bone-102	Characterize bone turnover and other biochemical markers of skeletal health.	Enabling/Utilization
Bone	Bone-201	Identify/develop/apply tools (e.g., computational modeling or alternative) to inform the estimation bone strength and probability of overloading bones and fracture assessment.	Enabling
Bone	Bone-301	Identify, develop, and implement monitoring tools for bone health during spaceflight.	Utilization
Bone	Bone-401	Identify and test preventative and mitigating countermeasures for changes induced by spaceflight.	Utilization
Bone	Bone-402	Validate countermeasures for maintaining preflight bone standard.	Utilization

RAP		GAP Description	Artemis Relevance
Cardiovascular	CV-101	Determine whether long-duration weightlessness and/or reduced gravity induces cardiovascular structural and functional adaptations that contribute to an increased risk of a cardiovascular event or and disease.	Enabling/Utilization
Cardiovascular	CV-102	Determine whether space radiation induces cardiovascular structural and functional adaptations and/or oxidative stress and damage (OSaD)/inflammation that contribute to an increased risk of a cardiovascular event or and disease.	Utilization
Cardiovascular	CV-103	Determine whether the combined effects of space radiation and altered gravity induce additive or synergistic effects on the cardiovascular system that contribute to an increased risk of a cardiovascular event or and disease.	Utilization
Cardiovascular	CV-202	Identify, develop, and test candidate countermeasures, including monitoring strategies, that prevent or mitigate spaceflight- and/or radiation-induced cardiovascular structural and functional adaptations in a spaceflight analog that contribute to an increased risk of a cardiovascular event and/or disease.	Enabling/Utilization
Cardiovascular	CV-203	Evaluate candidate countermeasures, including monitoring strategies, that prevent or mitigate spaceflight- and/or radiation-induced cardiovascular structural and functional adaptations in a spaceflight environment that contribute to an increased risk of a cardiovascular event and/or disease.	Utilization
Cardiovascular	CV-301	Validate an integrated countermeasure suite, including monitoring strategies, that prevent or mitigate the spaceflight- and/or radiation-induced cardiovascular structural and functional adaptations in a spaceflight environment that contribute to an increased risk of a cardiovascular event and/or disease.	Utilization

RAP		GAP Description	Artemis Relevance
EVA	EVA-101	Characterize EVA performance and preparedness shortly post-landing on a planetary surface.	Enabling/Utilization
EVA	EVA-102	Characterize surface EVA performance during exploration missions in partial gravity environments.	Enabling/Utilization
EVA	EVA-201	Characterize impacts of variable pressure exploration suits on EVA performance, including various exploration atmospheres and prebreathe strategies	Enabling/Utilization
EVA	EVA-301	Identify and test countermeasures related to spatial disorientation and motion sickness to enable early EVA's post g-transition.	Enabling/Utilization
EVA	EVA-302	Identify and test countermeasures to any physiological decrements associated with increased planetary EVA cadence (ie, exercise and nutrition)	Enabling/Utilization
EVA	EVA-303	Identify and test countermeasures related to exploration atmosphere impacts on hypoxia and decompression sickness.	Enabling/Utilization
EVA	EVA-401	Validate integrated EVA performance countermeasures related to optimizing physiological performance and minimizing DCS risk.	Enabling/Utilization

RAP		GAP Description	Artemis Relevance
Food and Nutrition	FN-101	Determine the nutritional requirements that would maintain health and performance for DRMs	Enabling
Food and Nutrition	FN-102	Determine the nutrient content, safety, and acceptability of the spaceflight food system (specific to each DRM and associated vehicle constraints).	Enabling/Utilization
Food and Nutrition	FN-201	Develop countermeasures either within the food system (i.e. variety, process improvements, crop growth, etc.) or in addition to (i.e. supplementation, etc.) to mitigate decrements in nutrition status, mitigate DRM impacts on health and performance outcomes, and/or risks to food safety, stability, and/or acceptability	Enabling/Utilization
Food and Nutrition	FN-302	Validate CM in flight	Utilization

RAP		GAP Description	Artemis Relevance
Immune	IM-106	Characterize the effect of the stressors associated with spaceflight (stress, microgravity, radiation, altered nutrition, circadian misalignment, hypoxia, etc.) on human immunity, determine clinical relevance and biomarkers to enable monitoring of astronauts.	Enabling/Utilization
Immune	IM-201	Based on immune dysfunction biomarkers identified in gap IM-106, identify, develop, and implement in-flight immune function monitoring tools for support of research during Gateway, Lunar, and Mars missions	Utilization
Immune	IM-501	Test the finalized, integrated, multi-component immune countermeasure in flight	Utilization
Microhost	Micro-101	Evaluate the effects of isolation, confinement and weightlessness on changes in the vehicle microbiome, the human microbiome, and microbial virulence	Utilization
Microhost	Micro-201	Evaluate the contribution of changes in microbial numbers, types, and virulence on the likelihood and consequence of adverse health events (infection), during the mission.	Utilization
Microhost	Micro-301	Identify, develop, and implement in-flight microbial monitoring/diagnostic tools for support of research and crew health during Gateway, Lunar, and Mars missions	Utilization
Microhost	Micro-401	Test, optimize and validate existing terrestrial or novel technologies that can maintain in-flight microbial counts, types, and virulence at terrestrial equivalent levels.	Utilization

RAP		GAP Description	Artemis Relevance
SANS	SANS-101	Determine the relationship between fluid shifts (intravascular, interstitial, CSF) and ocular manifestations in astronauts during spaceflight.	Utilization
SANS	SANS-102	Determine the relationship between fluid shifts-induced ocular changes and fluid shifts in the CNS, including whether elevated intracranial pressure or brain edema play a role.	Utilization
SANS	SANS-104	Determine whether ocular manifestations can be induced by fluid shifts in animal models and whether this model can be used for more detailed mechanistic insights.	Enabling
SANS	SANS-201	Determine if altered atmospheric conditions (e.g., elevated ambient CO_2, hypoxia from exploration atmosphere) has a contributing role in the development of ocular manifestations.	Utilization
SANS	SANS-203	Determine if radiation has a contributing role in the development of ocular manifestations	Utilization
SANS	SANS-403	Test candidate countermeasure(s) in a space flight environment.	Utilization
SANS	SANS-501	Validate/optimize integrated countermeasures in the spaceflight environment.	Utilization

RAP		GAP Description	Artemis Relevance
Sensorimotor	SM-101	Characterize the effects of short and long-duration weightlessness, with and without deep-space radiation, on postural control and locomotion (gross motor control) after G transitions.	Enabling/Utilization
Sensorimotor	SM-102	Characterize the effects of short and long-duration weightlessness, with and without deep-space radiation, on manual control (fine motor control) after G transitions.	Enabling/Utilization
Sensorimotor	SM-103	Characterize the effects of short and long-duration weightlessness, with and without deep-space radiation, on spatial orientation and motion sickness after G transitions.	Enabling/Utilization
Sensorimotor	SM-104	Evaluate how weightlessness-induced changes in sensorimotor/vestibular function relate to and/or interact with changes in other brain functions (sleep, cognition, attention).	Enabling/Utilization
Sensorimotor	SM-201	Develop and test postural control and locomotion countermeasures, including human factors aids.	Enabling/Utilization
Sensorimotor	SM-202	Develop and test manual control countermeasures, such as vibrotactile assistance vest, and other human factors aids	Enabling/Utilization
Sensorimotor	SM-203	Develop and test SMS countermeasures.	Enabling/Utilization
Sensorimotor	SM-204	Develop and test post-planetary-landing self-administered testing and rehab tool.	Enabling/Utilization
Sensorimotor	SM-301	Test the finalized combined CM Suite in flight.	Enabling/Utilization

RAP		GAP Description	Artemis Relevance
Cancer	Cancer-303	Identify early surrogate biomarkers that correlate with cancer, pre-malignancy, or other hallmarks of cancer	Enabling/Utilization
Cancer	Cancer-402	Identify and/or develop monitoring tools to support spaceflight research, long-term health surveillance, and countermeasure implementation	Enabling/Utilization
Cancer	Cancer-602	Operationalize identified interventional countermeasures	Enabling/Utilization
Cancer	Cancer-603	Operationalize identified monitoring/preventative countermeasures	Enabling/Utilization