TAPER:

Technology Advancing
Phobos Exploration & Return

Inspiration

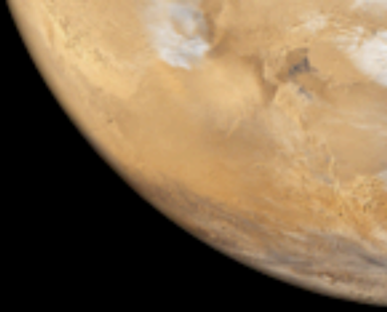
"He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me."
-Thomas Jefferson

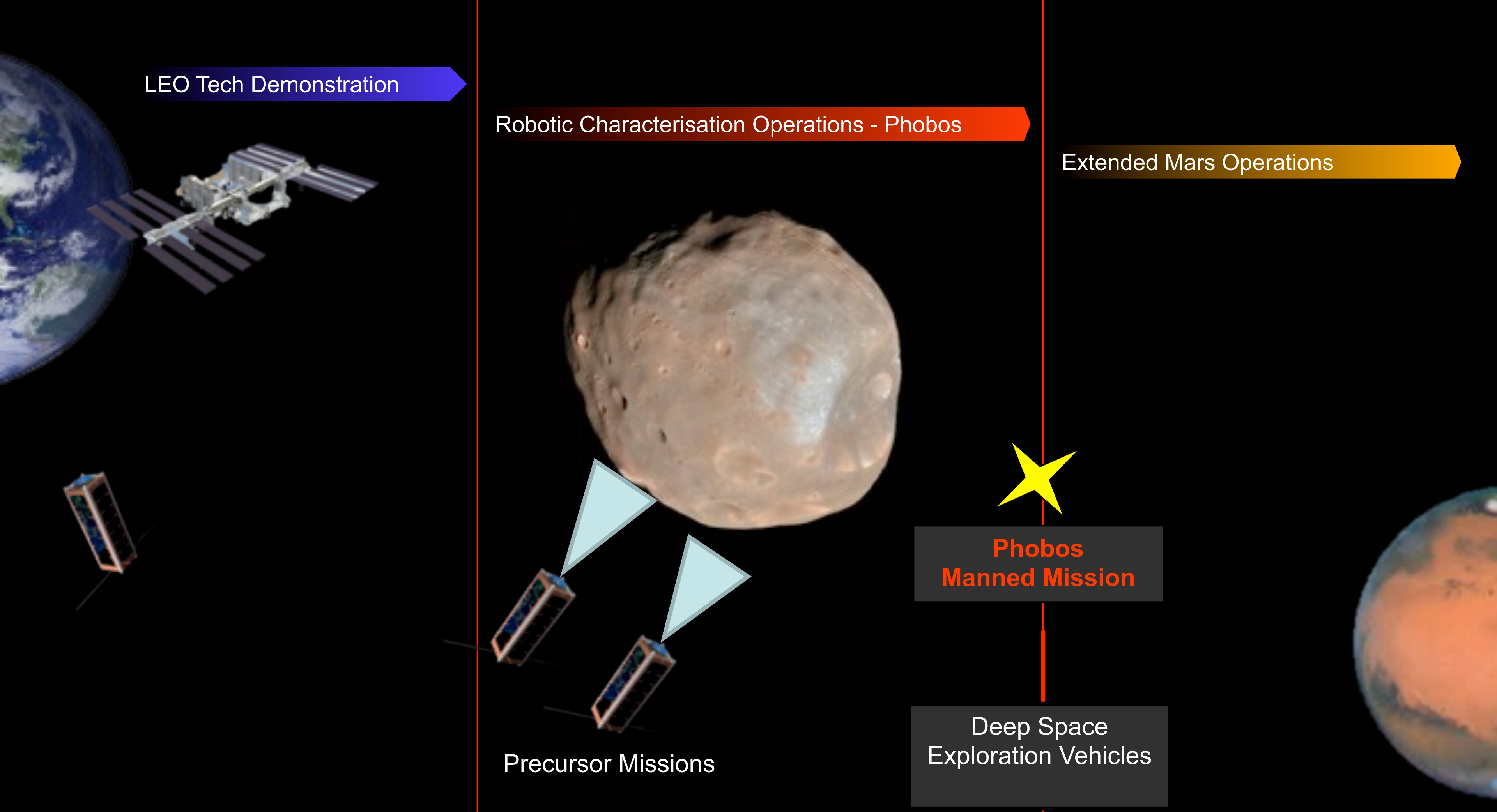
Presentation Roadmap

1. Execution & Administration (Chris Nie)
2. Science (Abigail Fraeman)
3. Engineering
   1. Mission Profile, Launch Dates, and Trajectory (Natasha Bosanac)
   2. Spacecraft Design & Layout (Frans Ebersohn)
   3. Propulsion Systems & Launch Capability Requirements (Frans Ebersohn)
4. Human Factors (Stefanie Gonzalez)
5. Conclusion (Nick Sweet)

TAPER - The Road Map to Mars

Technology Advcancing Phobos Exploration and Return (TAPER) is a concept program that aims to bridge the policy, technology, and science gaps for manned exploration of Mars by sending a crew to a Martian moon.





KEY ENABLING CAPABILITIES

- Satellite size decrease and capability increase
- Heavy lift launch vehicles
- Composite propellant tanks
- Zero boil-off technology

- High resolution topography, gravitational field, radiation, thermal, mineralogical and chemical composition mapping of Phobos.
- Examine the geotechnical and mechanical properties of the regolith.
- Examine the dust and regolith content.
- Search for subsurface ice/ volatile products

- Mars Surface ISRU
- Mars Sample Return
- Manned Mars Exploration

Mission Overview

Mission Statement

The mission of TAPER 1 is to send an **international crew of four to Phobos** and return them safely with **surface samples** to serve as **precursor** to the human exploration of Mars.

Objectives

- Demonstrate the **ability** to **send humans to the martian system** and return them safely with samples of the environment;
- Assess the **feasibility** of **Phobos** as **resources** for future missions to the martian surface;
- Investigate the **origin** and **evolution** of the moons to better understand the **martian system**;
- Understand the **current environment of Phobos** in the context of the martian system to **support** architecture for **future manned Mars missions**.
- **Establish infrastructure on Phobos** to support future manned exploration of both Phobos and Mars.

Mission Timelines

Opposition Class Mission

LEO Technology Demonstration using the International Space Station : January 2015

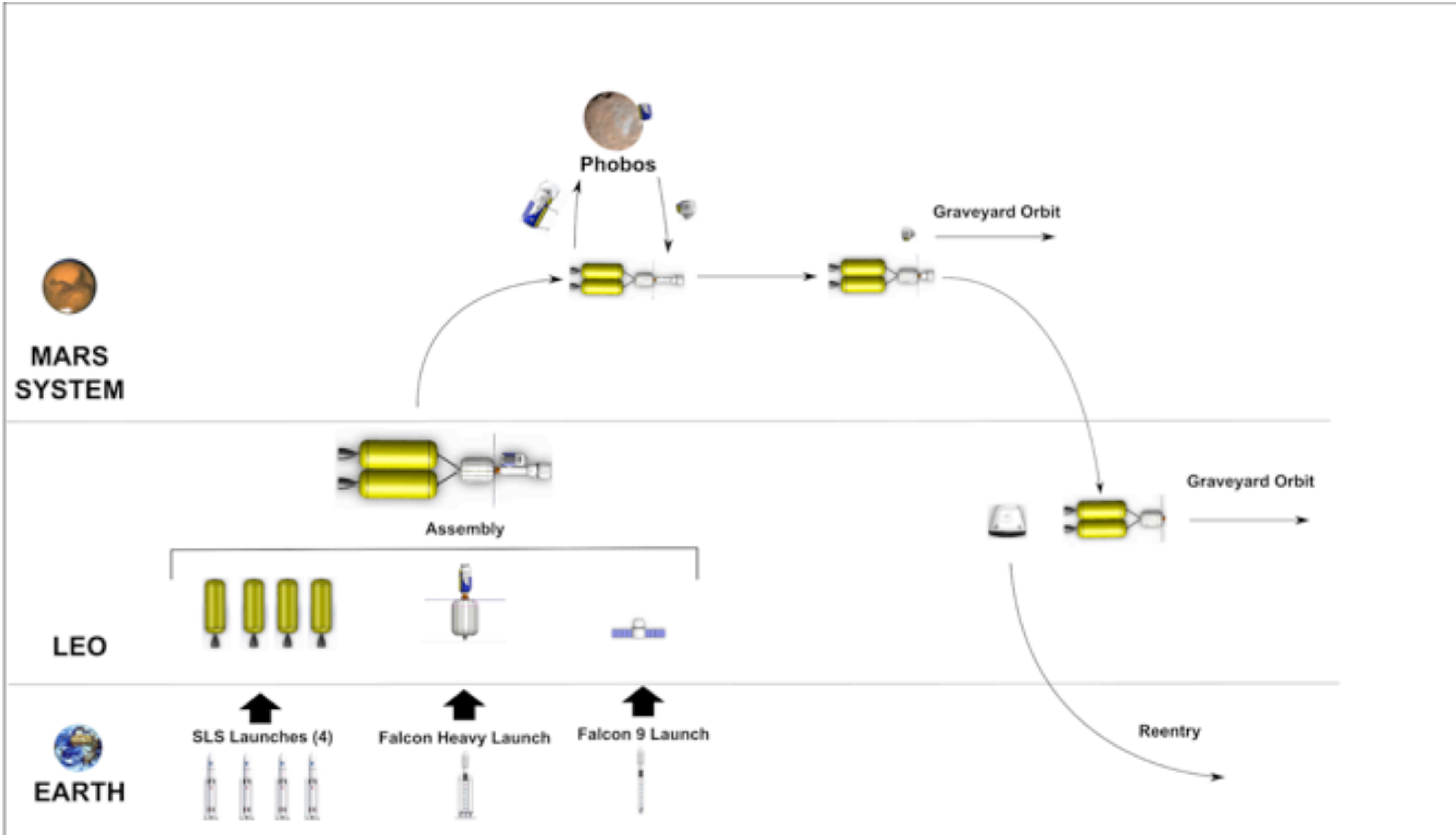
Nominal Precursor Mission: October 2024 - July 2026

Contingent Precursor Mission: August 2026 - May 2028

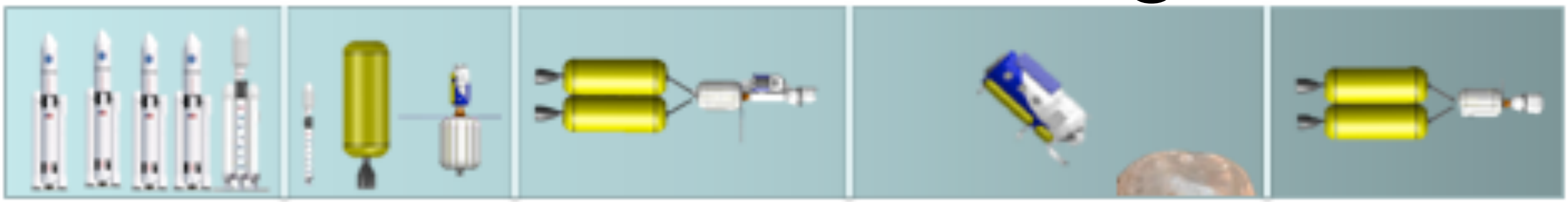
Nominal TAPER Mission: March 2033 - July 2034

Contingent TAPER Mission: August 2035 - October 2036

Mission Architecture



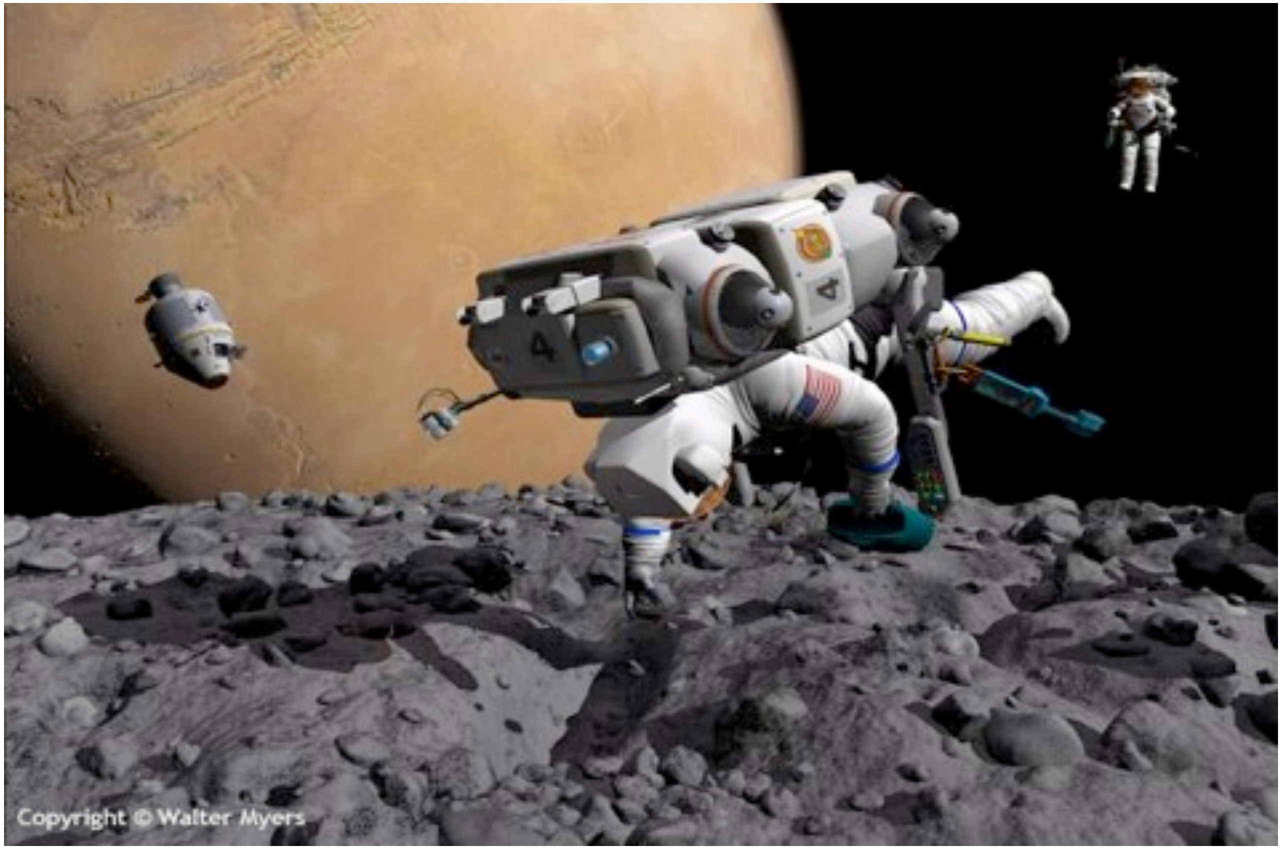
Mission Phasing



Phase I: Cargo Launch Approx: T-30 to T-1	Phase II: LEO Assembly T+0 to T+2	Phase III: Phobos Transit T+3 to T+183	Phase IV: Phobos Vicinity T+184 to T+207	Phase V: Earth Return T+208 to T+441

- Phase I:
  - Launch and transit of cargo to Low Earth Orbit (LEO)
- Phase II:
  - LEO Assembly of transit stage
- Phase III:
  - Interplanetary transfer to Mars vicinity
  - Experimentation
- Phase IV:
  - Martian and Phobos orbit injection
  - PSE undock and landing on Phobos
  - Surface operations (detailed later)
- Phase V:
  - Interplanetary transfer to Earth vicinity
  - Sample down select
  - Experimentation

Science



Why Phobos?

Strategic Knowledge Gaps

1. Map the global topography of Phobos.
2. Measure the gravitational field in the local vicinity of Phobos.
3. Assess the radiation properties in the local vicinity of Phobos.
4. Map and assess the mechanical properties of the regolith on Phobos.
5. Examine the mechanical and electrostatic properties of the dust and regolith on the surface of Phobos.
6. Search for subsurface ice and other volatile products.
7. Map the thermal environment of Phobos.
8. Map the global mineralogical and chemical composition of Phobos.

Can be addressed by NASA Discovery class mission(s)

Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system

- Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation
- Determine composition in situ of rocks and regolith from diverse and well characterized locations
- Constrain internal structure of Phobos
- Characterize Phobos regolith and processes that may have modified it over time

Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system

2. Assess availability of in situ resources for possible future use in manned Mars missions

- Determine is the volatile content of the moon's surface and subsurface
- Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE

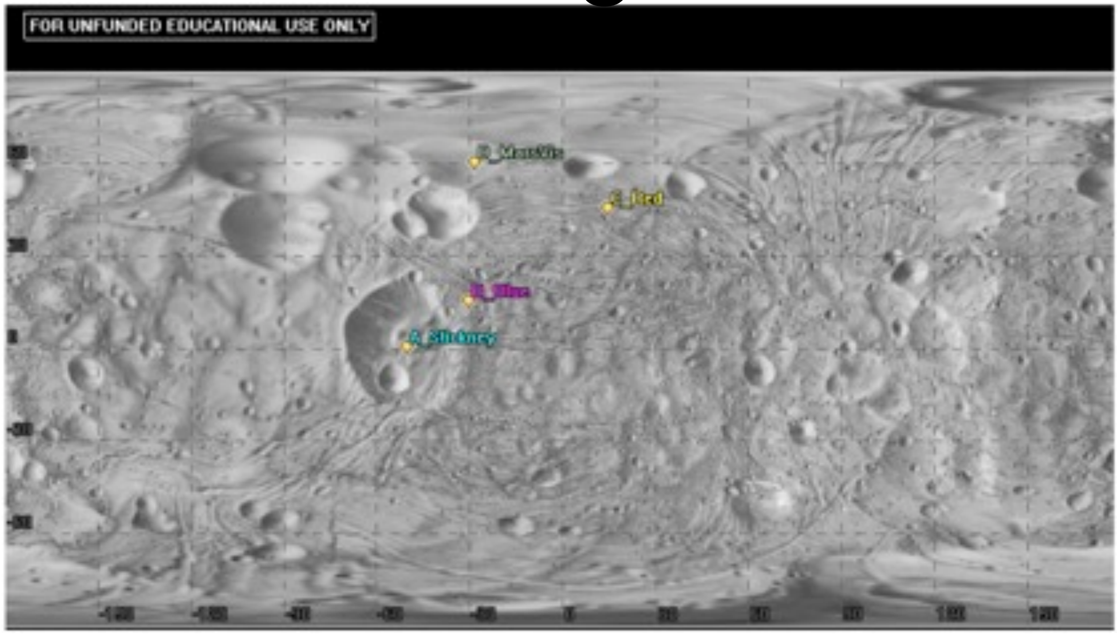
Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system
2. Assess availability of in situ resources for possible future use in manned Mars missions
3. Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions
- Characterize effects of space weathering on the Phobos' regolith
- Understand how radiation is attenuated and blocked on the surface over time
- Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos

Science Traceability Matrix

Science Related Mission Objectives	Measurement Objectives	Measurement Requirements	Instrument Requirements
Investigate the origin and evolution of the moons to better understand the Martian system	Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation	Rock and soil samples must be collected from at least two locations on Phobos (red and blue units), preferrably three	Returned samples to be analyzed by techniques on Earth including XRD, isoptoic/age dating analyses, etc.
	Determine composition in situ of rocks and regolith from diverse and well characterized locations	Rock and soil samples must be investigated from at least two locations on Phobos (red and blue units), preferrably three	Raman/LIBS, Visible/Near infrared spectrometer measurements; Multispectral camera to identify spectrally unique areas and provide context
	Constrain internal structure of Phobos	Seismic measurements locations across Phobos	Deployable Seismometers
	Characterize Phobos regolith and processes that may have modified it over time	In situ science to characterize grain size/distribution/ roundness; investigation of returned core samples	Hand lense, corer and scoop to bring back regolith samples
Assess availability of in situ resources for possible future use in manned Mars missions	Determine is the volatile content of the moon's surface and subsurface	Measure regolith water content in situ, collect sample cores from any areas indentified by precursor as potential for having subsurface water	Raman/LIBS, VNIR spectrometer, Neutron spectrometer, drill for areas identified by precursor mission as potential for subsurface ice; deep drill if indicated necessary by precursor science
	Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE	Understand composition of surface	Raman/LIBS, APXS, Visible/Near infrared spectrometer measurements
Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions	Characterize effects of space weathering on the Phobos' regolith	Collect core samples from at least three locations on each of two sites	Returned samples: XRD, isoptoic and age dating analysis, GCMS, etc.
	Understand how radiation is attenuated and blocked on the surface over time	Measure fluxes and energies of particles received at Phobos surface	Plasma wave detector; energetic particle detector for high and low energy particles
	Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos	Measure dust fall on Phobos	Dust detector

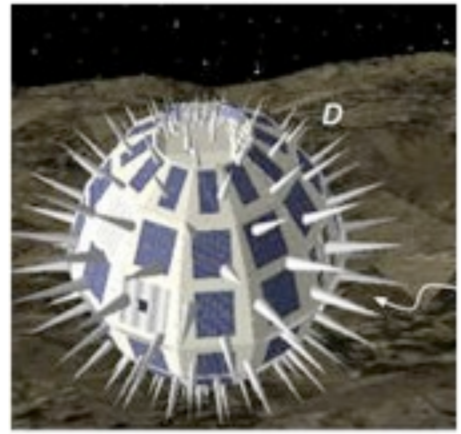
Landing Sites

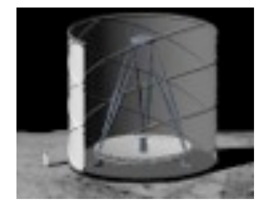


Site Identifier	Site Location	Coordinates	Distance from previous site [km]
A	Stickney crater	50 deg W, 0 deg N	0
B	Blue spectral unit	30 deg W, 15 deg N	6
C	Red spectral unit	15 deg E, 45 deg N	11
D	Mars Visible	28 deg W, 60 deg N	9

Science Payload: *In Situ* Science

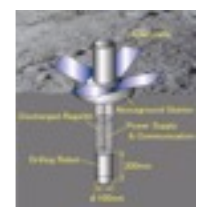

Sample collection equipment

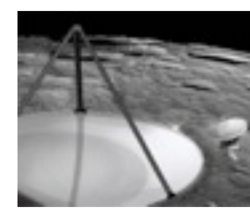

Mobile Science Platforms "Phobots"




Seismic Array with ChipSats

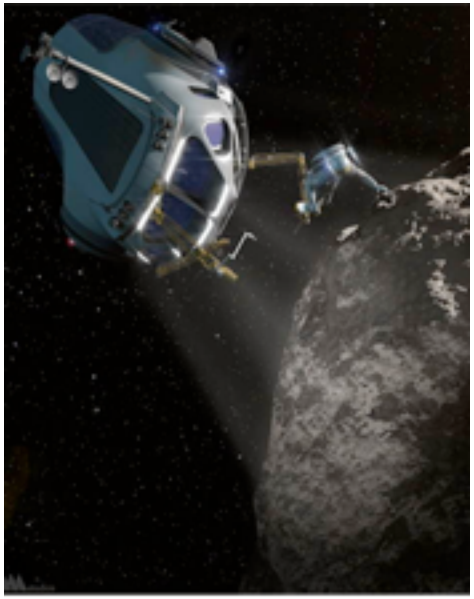

Space Weather Stations



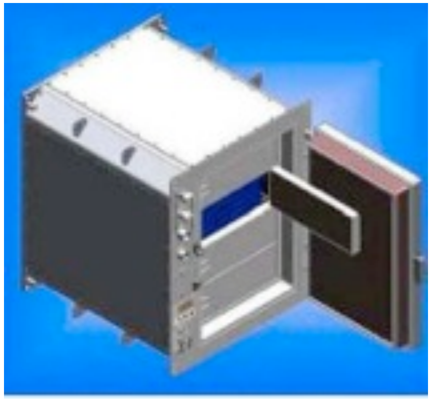

Mass margin left for new instruments based on precursor science results

Surface science equipment	Heritage	Qty	Mass (kg)
Sample collection equipment		1	425
Robonauts		2	100
Tongs, rake, dust scooper, hammer, hand lens, documentation camera		1	25
Sample boxes, cores, bags		1	200
Mobile Science Platforms (Typical payload below)		5	10
Raman/LIBS Spectrometer	JPL Raman/LIBS in development	1	3
Multispectral imaging system	Rosetta Landing Imaging System (ROLIS)	1	0.5
Neutron spectometer	Dynamic Albedo of Neutrons (DAN)	1	3
Visible/Near-Infrared Spectrometer	Comet Infrared and Visible Analyzer System (CIVA)	1	0.75
Chasis + communications		1	2.75
Seismic network stations		25	1
Small networks deployed towards landing	JPL in development	5	1
Space weather stations		3	12.5
Plasma Wave System	FPMS		3
Micrometeorite Detector	METEOR		3.5
Dust Particle Detector	DIAMOND		3
Structure + comm system			3
Margin for additional instruments necessary by precursor science			300
Total + 20% margin			**1005**

Sample Collection Strategy



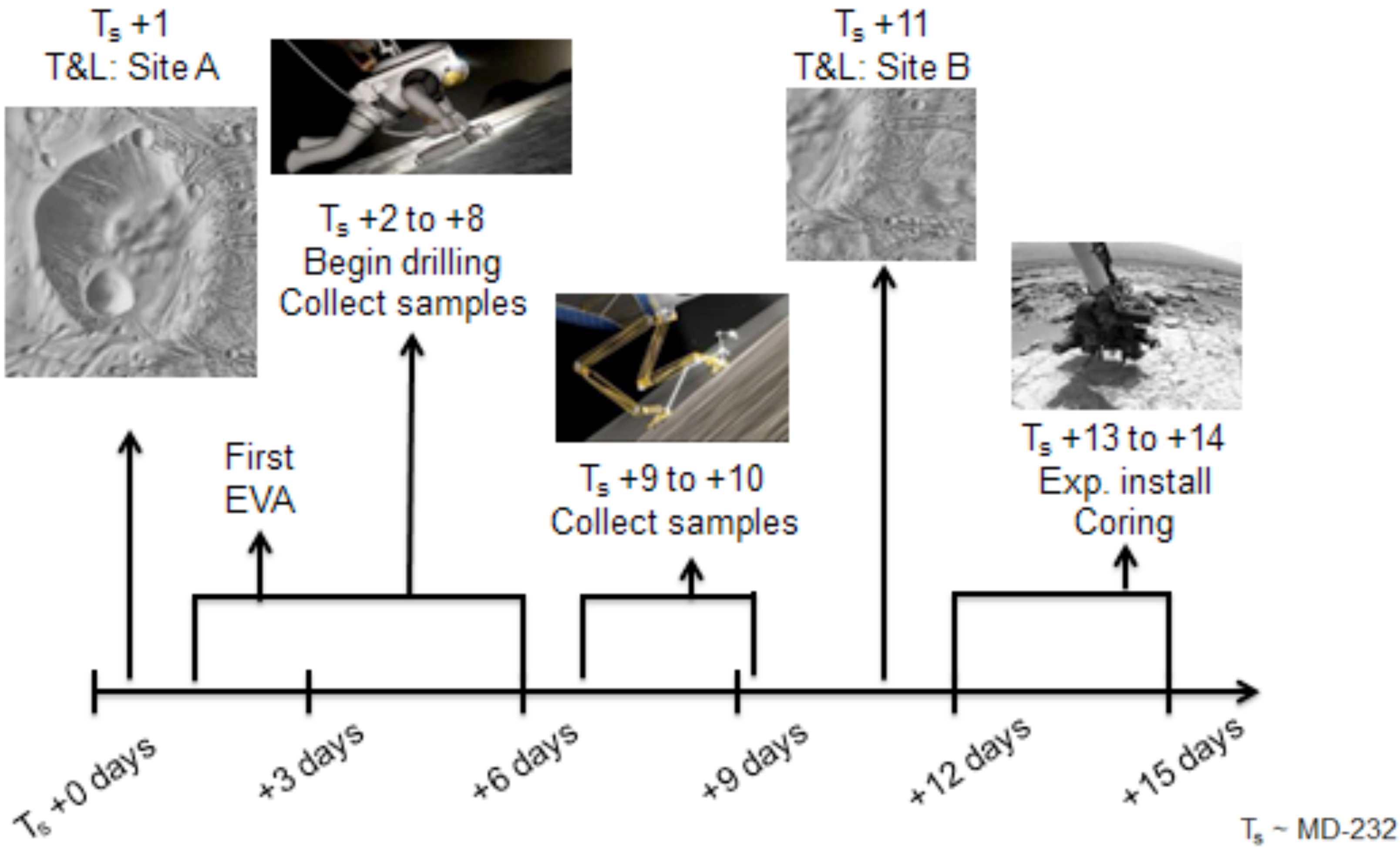
Samples will be collected from each of the 3 EVA sites.



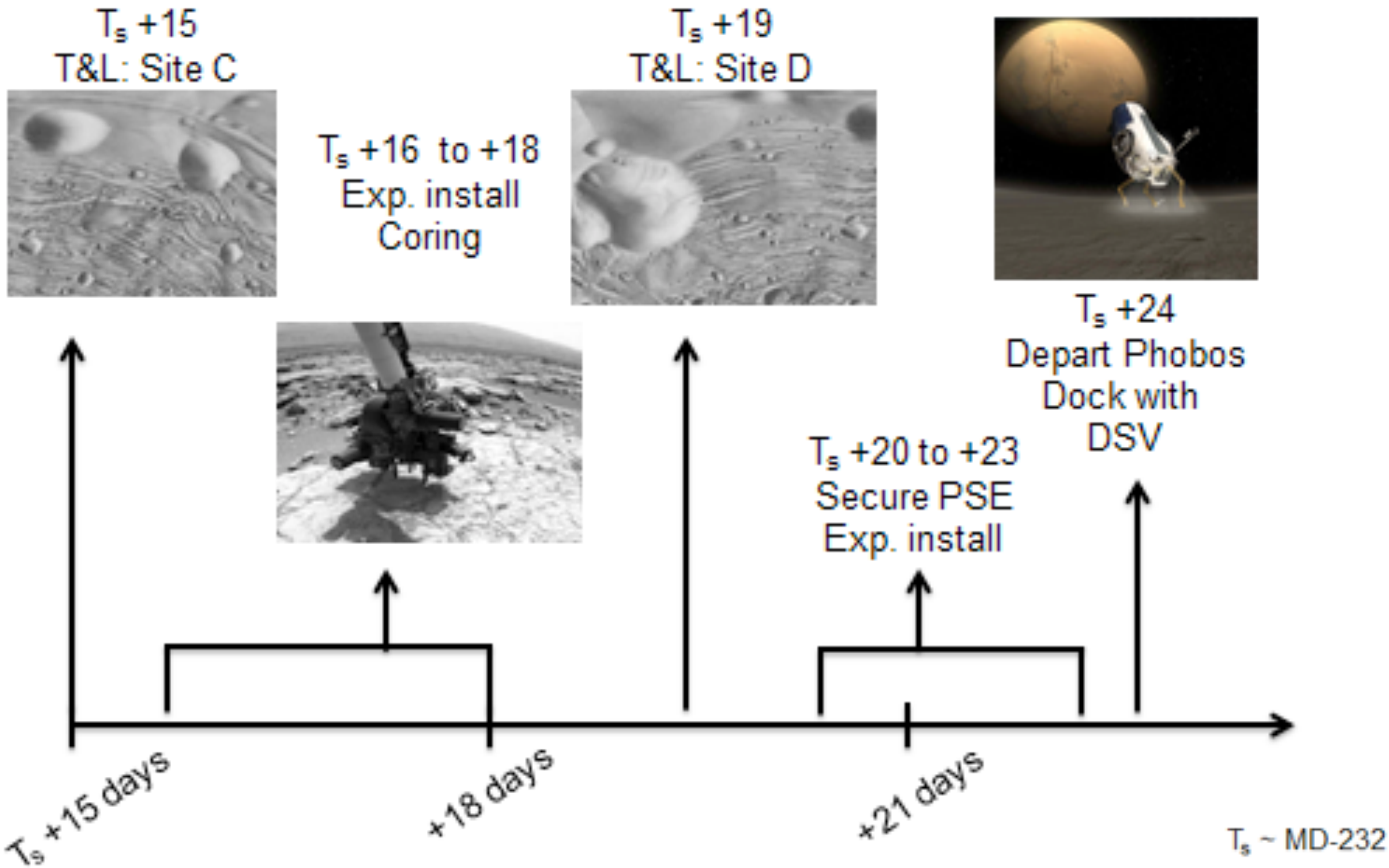
Artists conception of GLACIER, a possible precursor to types of cold storage required for samples possibly containing volatile material

	Rock samples	Core samples	Soil scoops
Required collected qty per EVA site:	30	10	5
Number of EVA sites:	3	3	3
Minimum mass per single sample (kg):	0.2	1.5	0.1
Total mass (kg) for all samples:	18	45	1.5
Total mass + margin for 10% E/PO, 20% international cooperation, 20% target of opportunity:	27	67.5	2.25

Surface Operations



Surface Operations



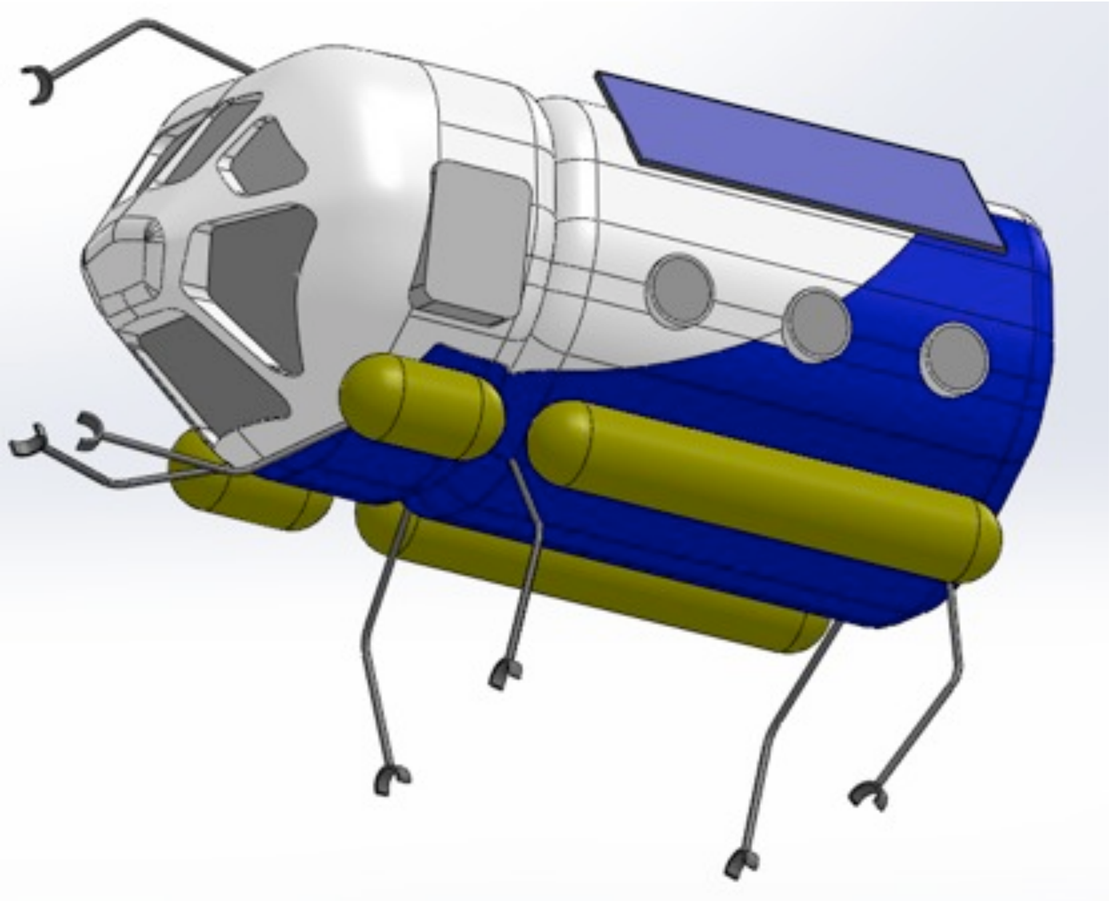
Science Payload: Additional Science

Orbital Remote Sensing Instruments	Heritage	Mass (kg)	Power (W)
High resolution multispectral imaging	Dawn framing camera	10	20
Radar	Sharad	15	40
Middle energy range particle detector	MARIE	4	7
Low energy range particle detector		2	2
High energy range particle detector		2	2
Cubesats sent to Deimos (x 5)		3	N/A
Dedicated instrument for		10	10
Total + 20% margin		69.6	97.2

Science in Transit

- Compositional and isotopic analysis of samples for triage
- Radiation experiments
  - New-LIFE
  - Dosimeters
  - Additional experiments designed to test the effects of long duration spaceflight on humans are described in section on human factors
- Provide outreach opportunity for the general scientific community to propose experiments and develop instrumentation for observations of Earth as an exoplanet

Engineering



Engineering Requirements

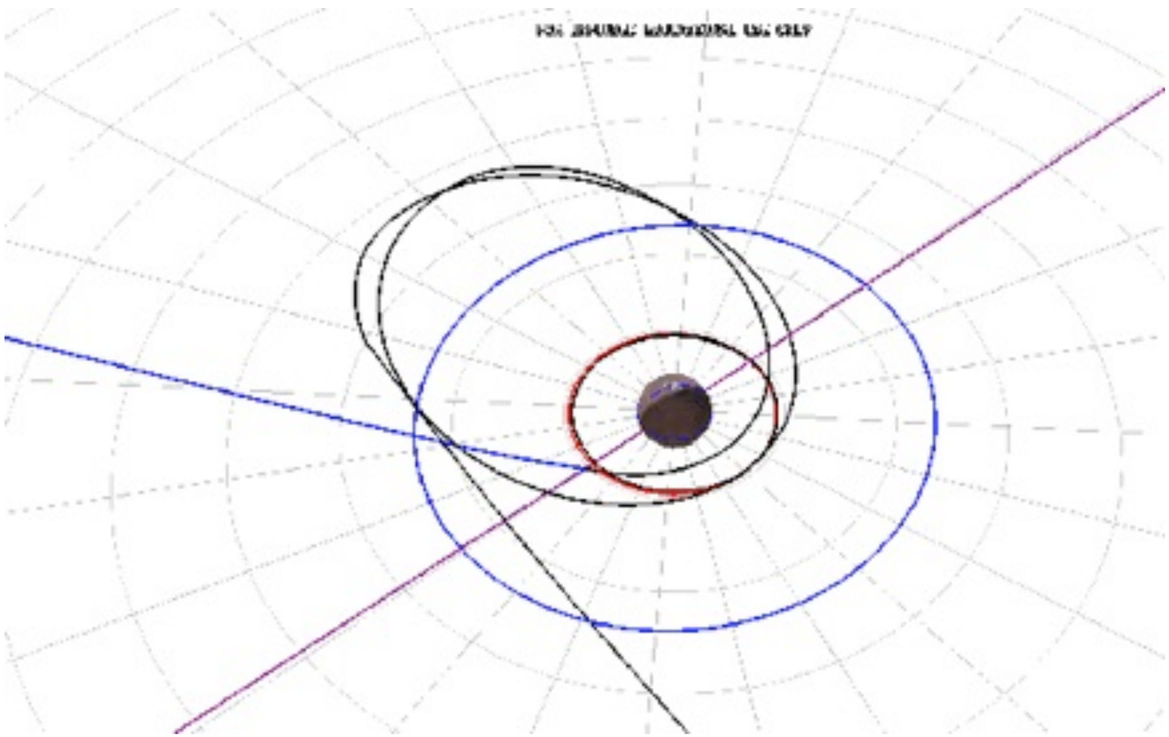
Top Level Requirements derived from Objectives

The crew shall remain safe for the mission duration.
The crew shall travel to Phobos and return.
The crew shall land on the surface of Phobos
The crew shall obtain samples from Phobos.
The mission shall satisfy the science goals
The mission shall demonstrate selected technologies
The mission shall comply relevant legal and Planetary Protection requirements.

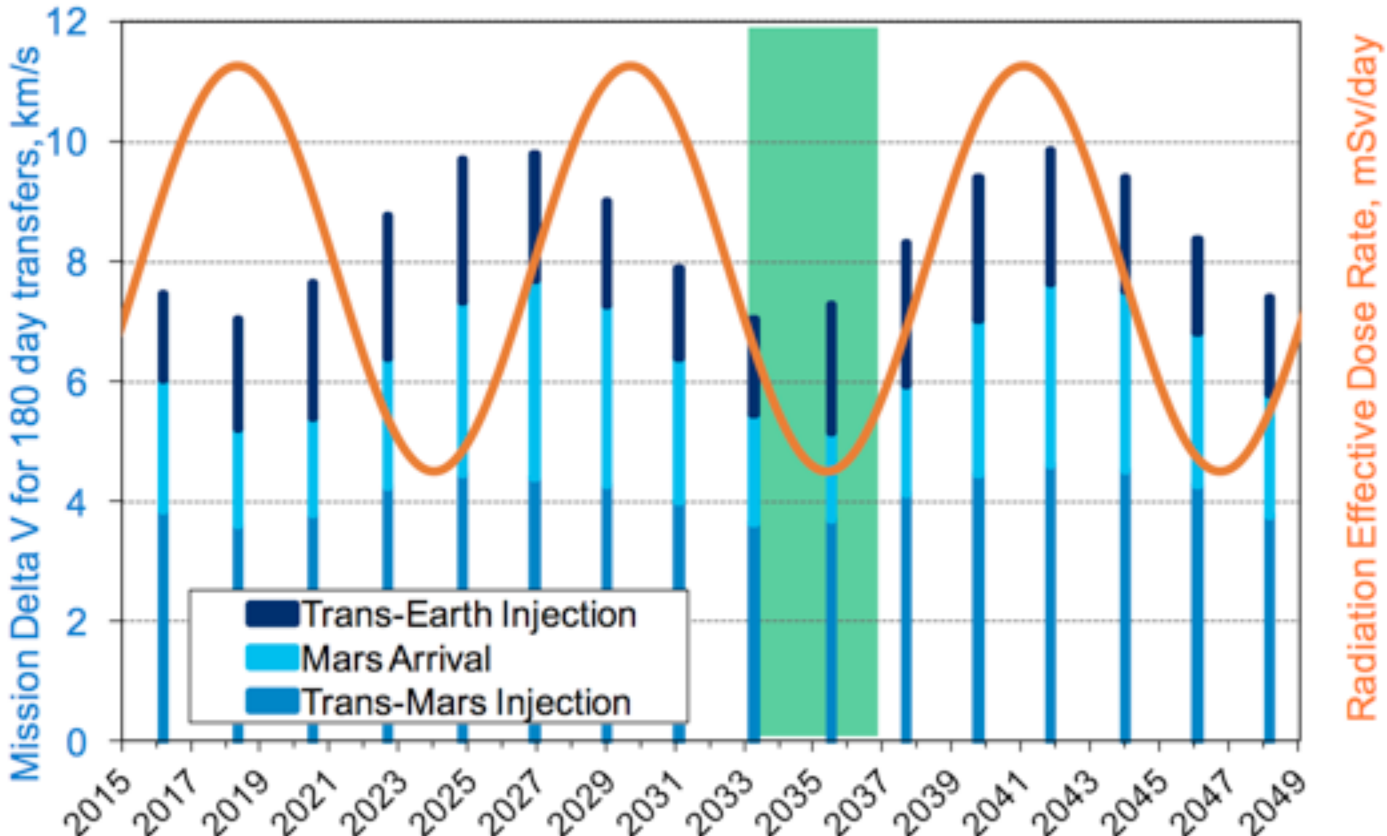
Subsystem level requirements

> Trajectory design, spacecraft design, propulsion system, human factors, power, communications, thermal control, AODCS & GNC

Mission Profile, Launch Dates, and Trajectory



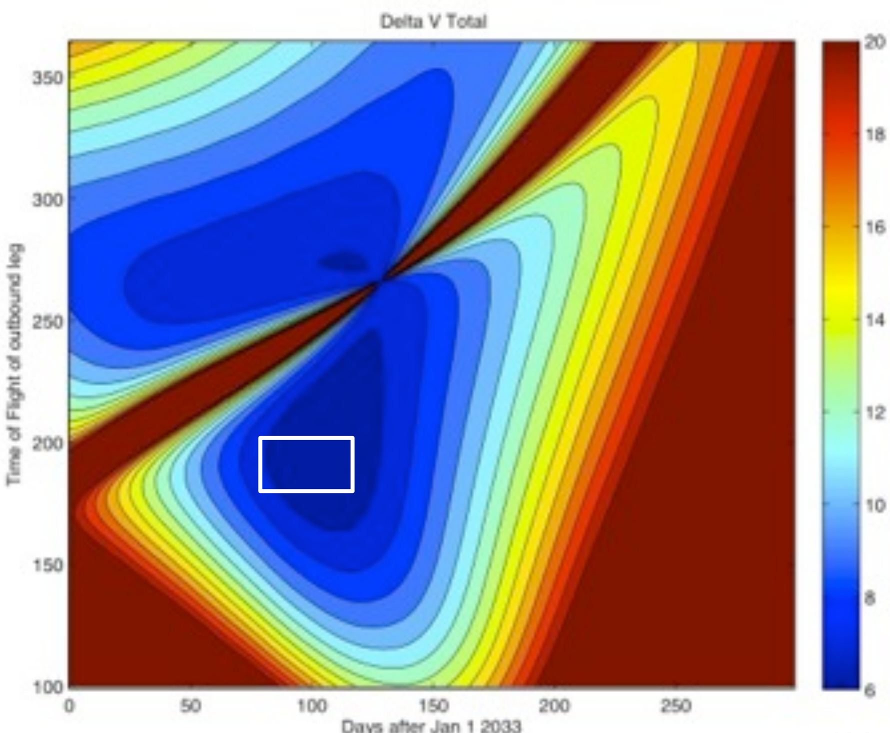
Selection of Crew Launch Year



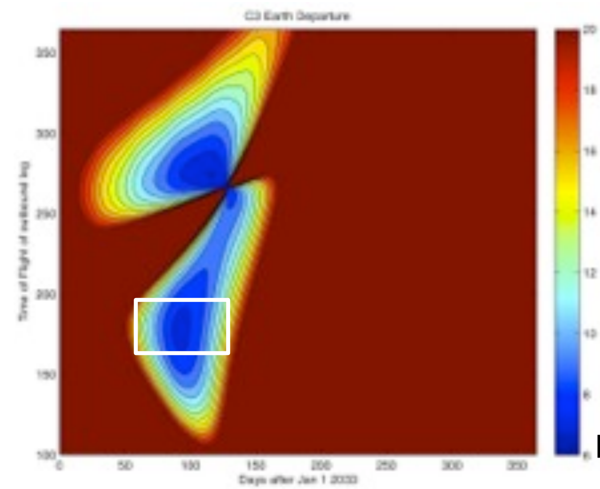
Selected Crew Launch Year: 2033
Backup Crew Launch Year: 2035

[Hopkins, 2013]

2033 Crew Earth Departure
Selection of Departure Date and TOF



ΔV
km/s

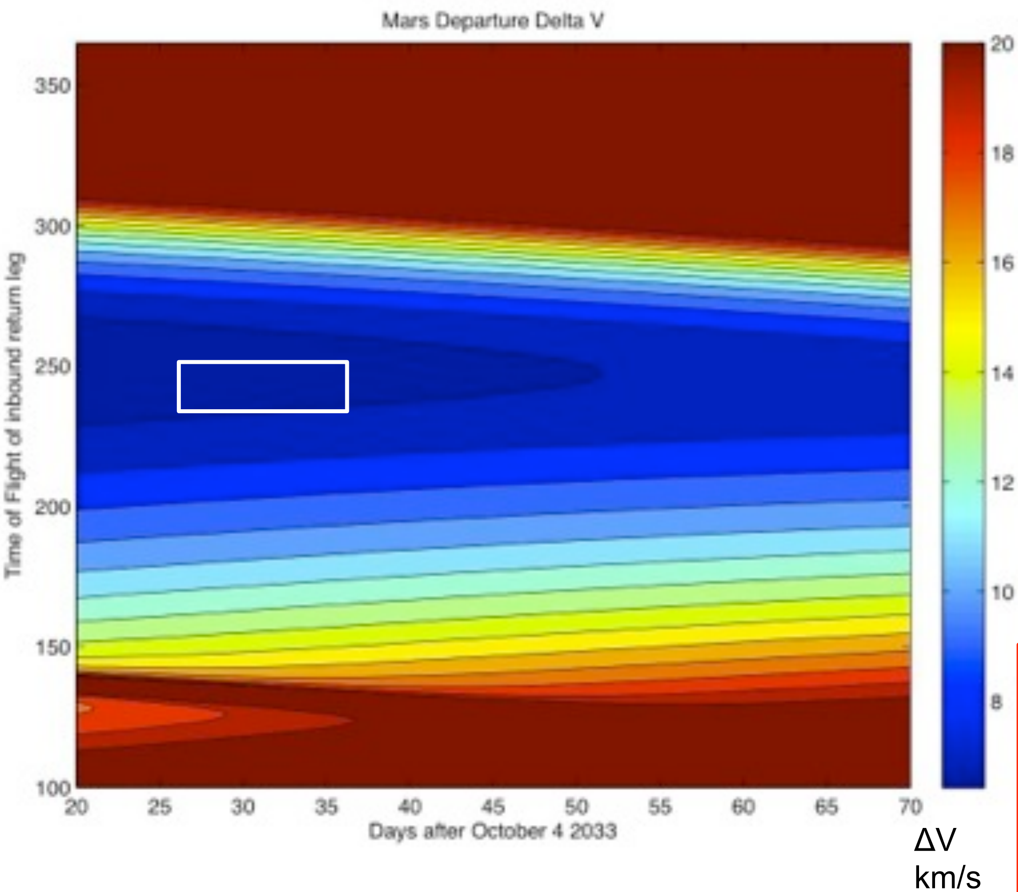


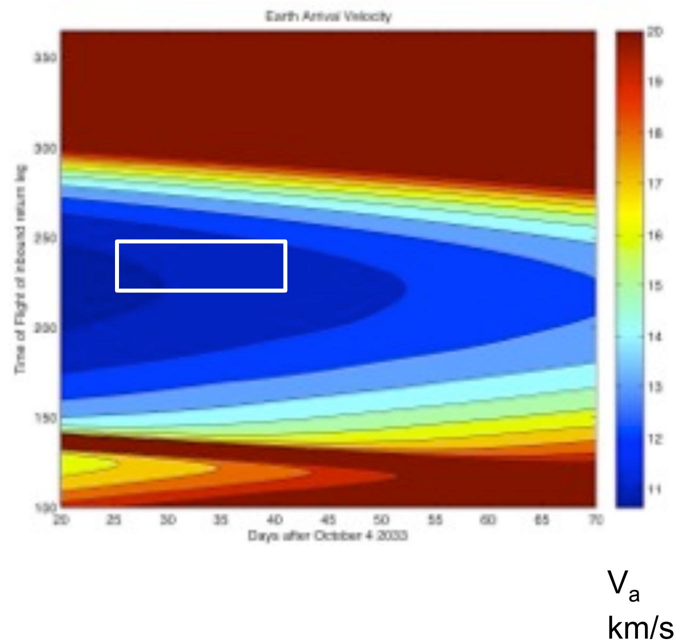
TOF : 180 days

Earth Departure: 7th April 2033
Mars Arrival: 6th October 2033

Crew Launch: 6th April 2033
Earth Departure Window (ΔV<6.8km/s):
1st April 2033 to 2nd May 2033

Crew Return Leg (2033 Launch) Mars Departure ΔV

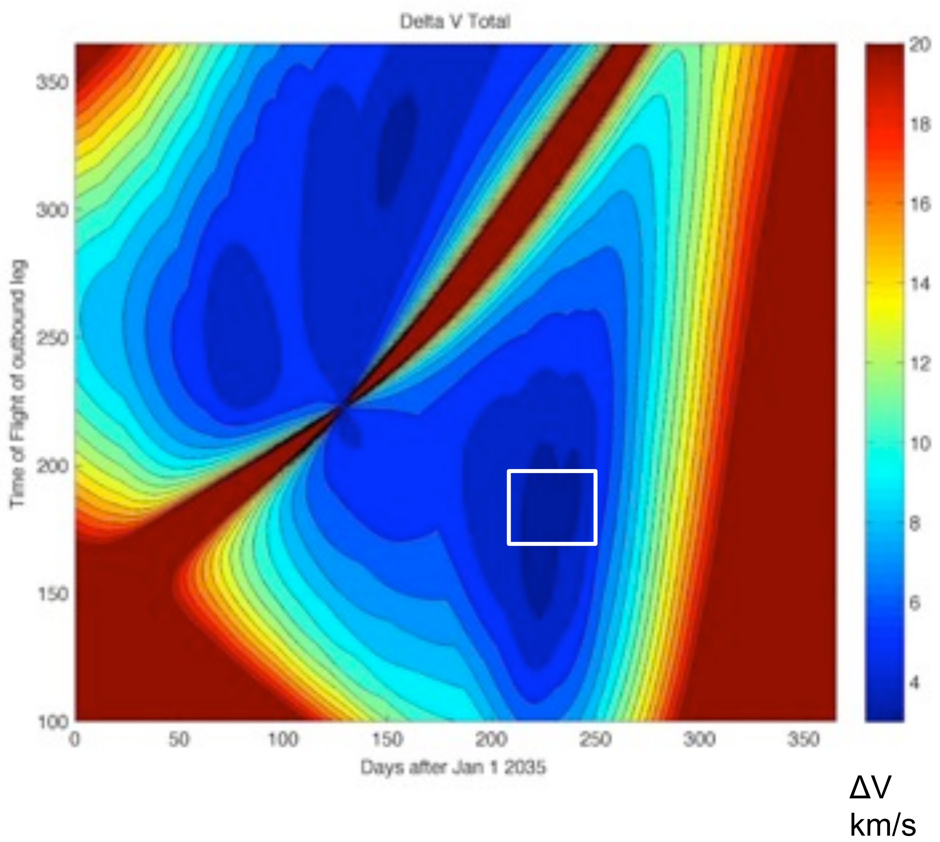




TOF : 246 days

Mars Departure: 2nd November 2033
Earth Arrival: 6th July 2034

2035 Crew Earth Departure Selection of Departure Date and TOF



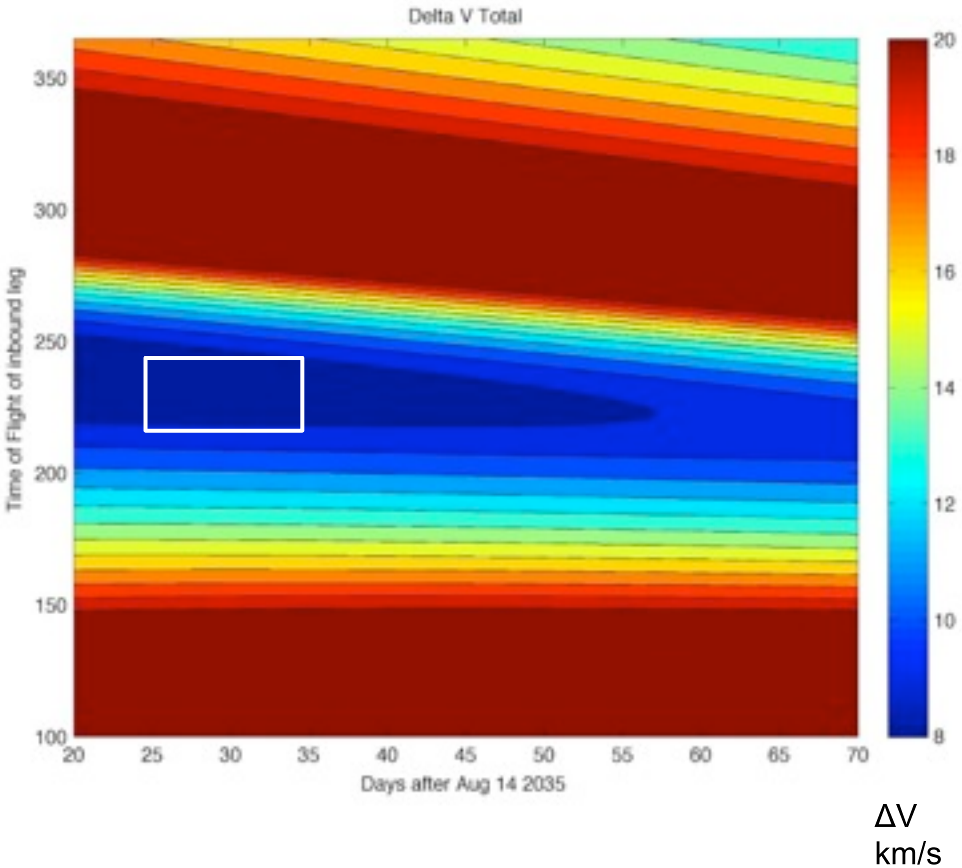
TOF : 180 days

Earth Departure: 14th August 2035
Mars Arrival: 10th February 2036

Crew Backup Launch:
13th August 2035

Earth Departure Window:
6th August 2035 to 20th August 2035

Crew Return Leg (2035 Launch)
Mars Departure Delta V



TOF : 233 days

Mars Departure: 11th March 2036
Earth Arrival: 30th October 2036

Crew Outbound Trajectory Overview

[Landau & Strange, 2013]

Phobos L_1 Lyapunov Orbit
Begin: 7 October 2033 End: 1 November 2033

Raise Periapsis:
Date: 6 October 2033, ΔV = 0.10 km/s, at apoapsis
Enter Phobos Orbit:
Date: 7 October 2033, ΔV = 0.57 km/s, at periapsis
Maintain: ΔV ~ 0.10 km/s

Phobos Orbit

Plane Change & Insertion into High Mars Orbit
Date: 6 October 2033
ΔV = 2.36 km/s, at crossing of Phobos orbit plane

High Mars Orbit

Periapsis: 9376 km. Apoapsis: 37000km Inclination=0 deg

Interplanetary Trajectory
Begin: 7 April 2033 End: 6 October 2033

C3 = 8.4 km^2/s^2 Right Ascension = 269 deg Declnation = -56 deg

Trans-Mars Injection from 300km LEO
Date: 7 April 2033
ΔV = 3.7 km/s performed at periapsis

LEO

300km Altitude, 28.5 degree inclination

Launch from Earth
Date: 6 April 2033

Earth

**All maneuvers are impulsive

Crew Inbound Trajectory Overview

Phobos L_1 Lyapunov Orbit
Begin: 7 October 2033 End: 1 November 2033

Raise Apoapsis:
Date: 1 November 2033, ΔV = 0.57 km/s, periapsis

Phobos Orbit

Lower Periapsis, Insertion into High Mars Orbit:
Date: 2 November 2033, ΔV = 0.07 km/s, apoapsis

High Mars Orbit

Trans-Earth Injection
Date: 4 November 2033, ΔV = 6.03 km/s

Periapsis: 9376 km. Apoapsis: 37000km Inclination=0 deg

Interplanetary Trajectory
Begin: 4 November 2033

C3 = 8.4 km^2/s^2 Right Ascension = 269 deg Declnation = -56 deg

LEO

300km Altitude, 28.5 degree inclination

Direct Earth Entry
Date: 6 July 2034 Entry velocity ~ 11.3 km/s

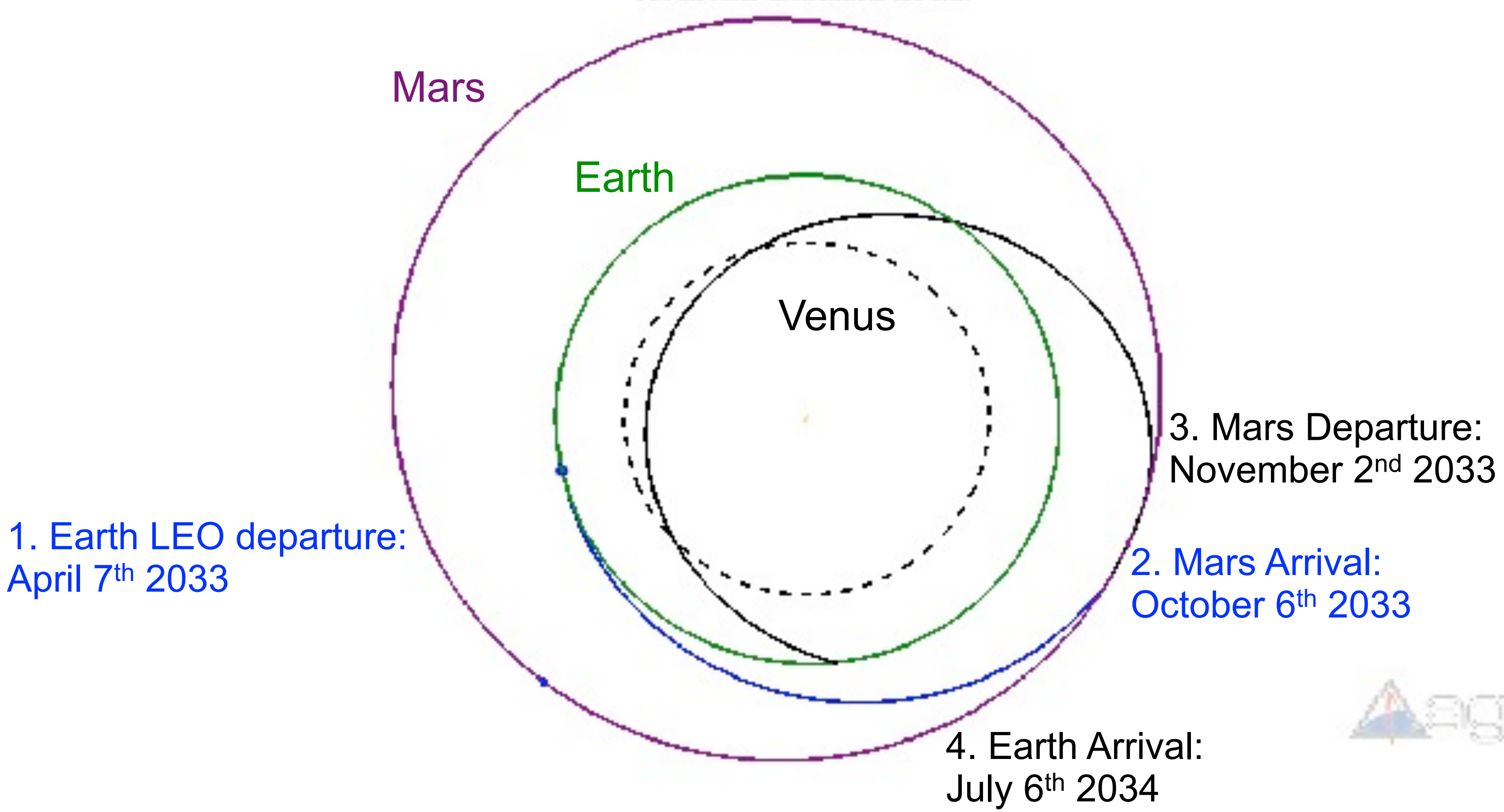
Earth

**All maneuvers are impulsive

Total Time of Flight: 456 days. Total ΔV = 13.5 km/s

Crew Outbound Trajectory

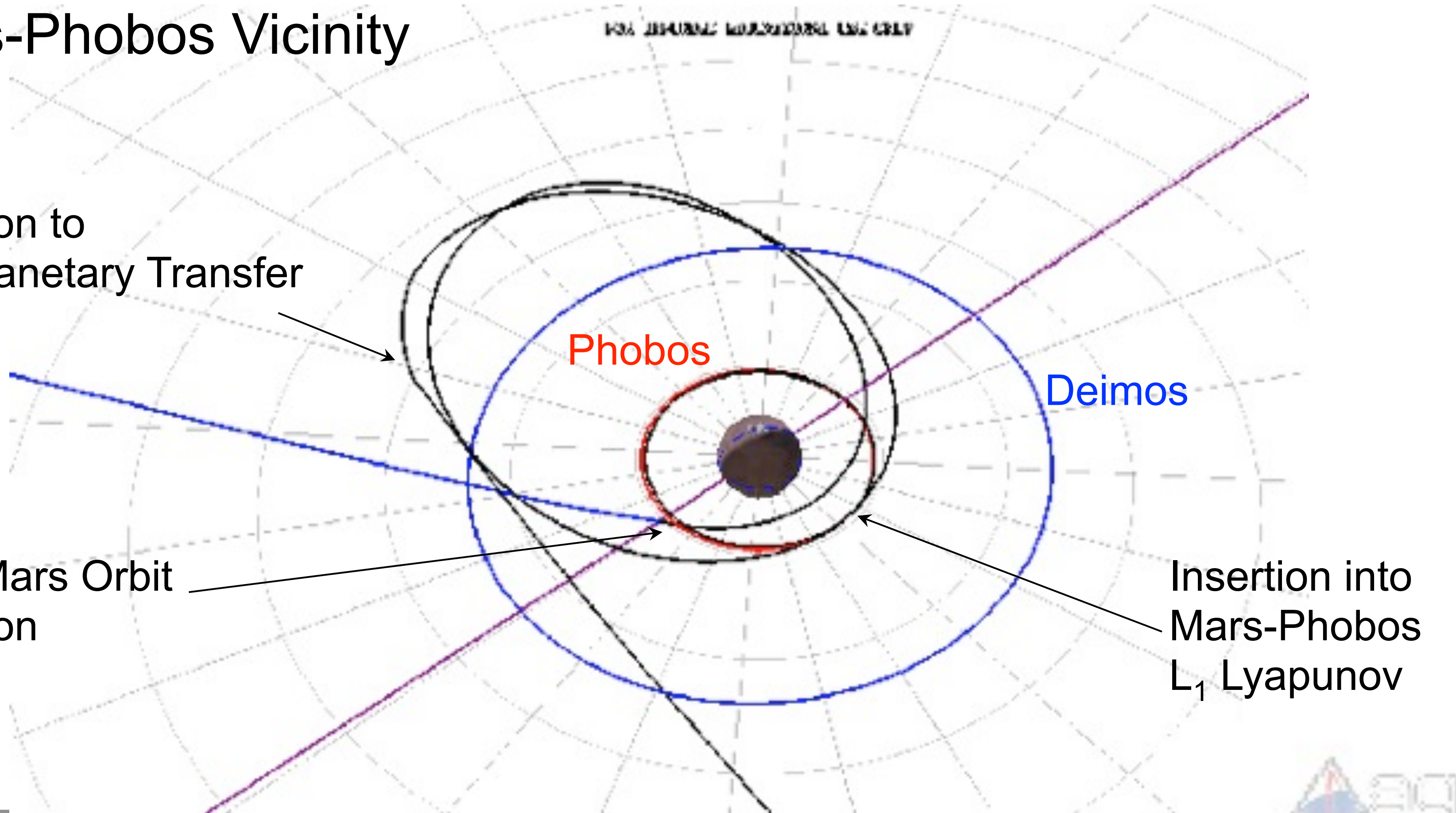
Interplanetary Transfer



Crew Outbound Trajectory

Mars-Phobos Vicinity

Insertion to
Interplanetary Transfer

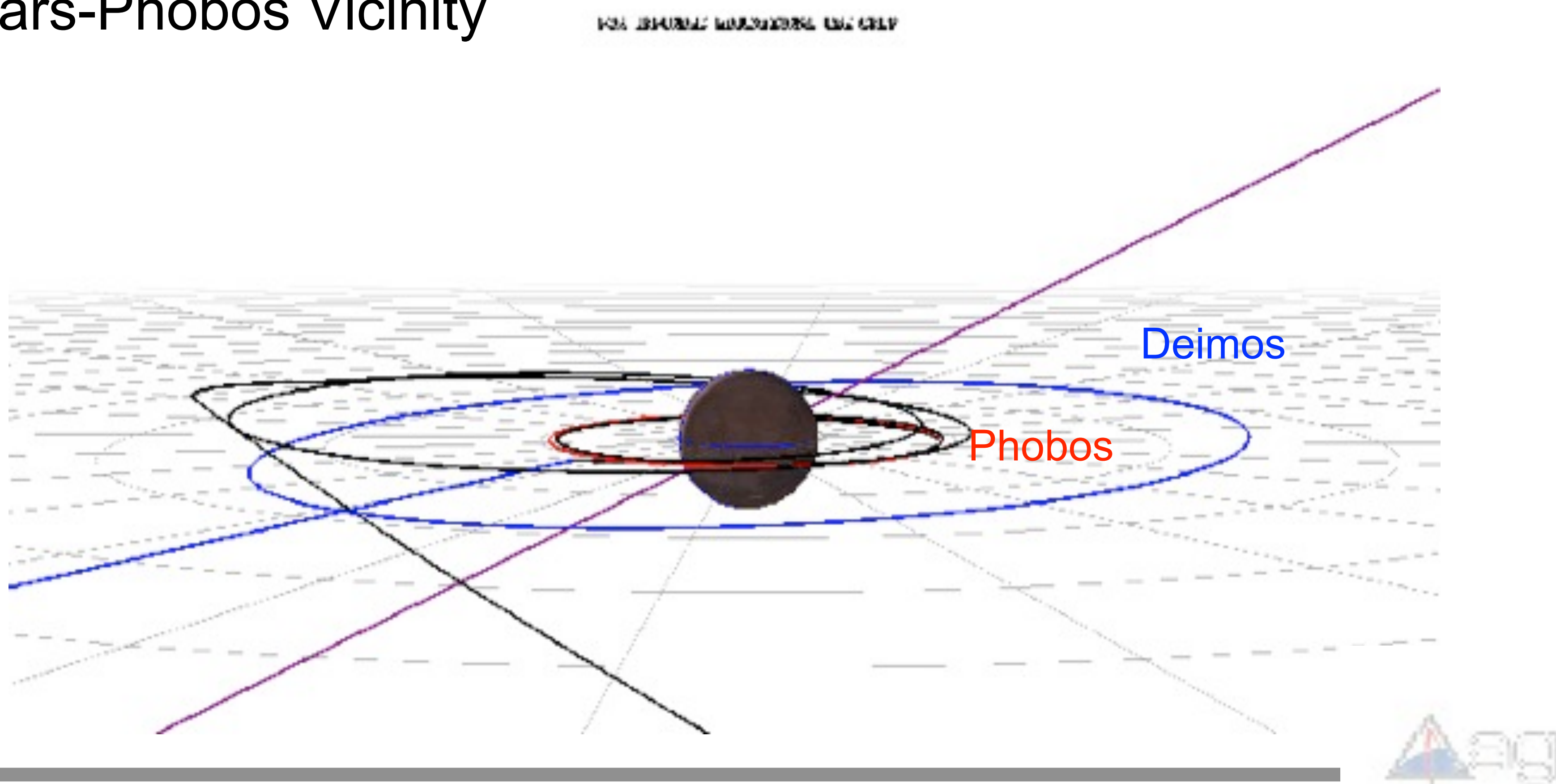


High Mars Orbit
Insertion

Insertion into
Mars-Phobos
L_1 Lyapunov

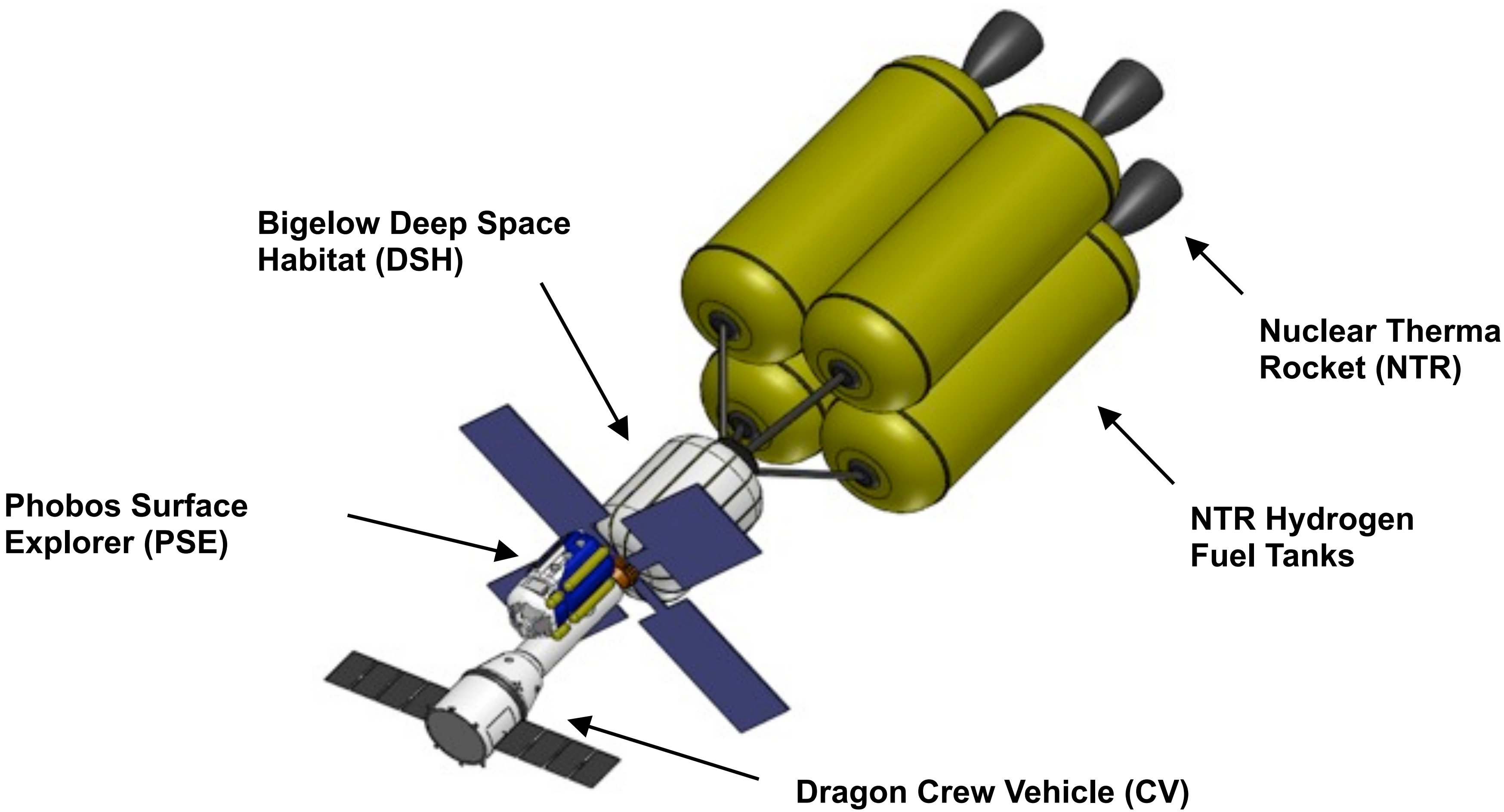
Crew Outbound Trajectory

Mars-Phobos Vicinity

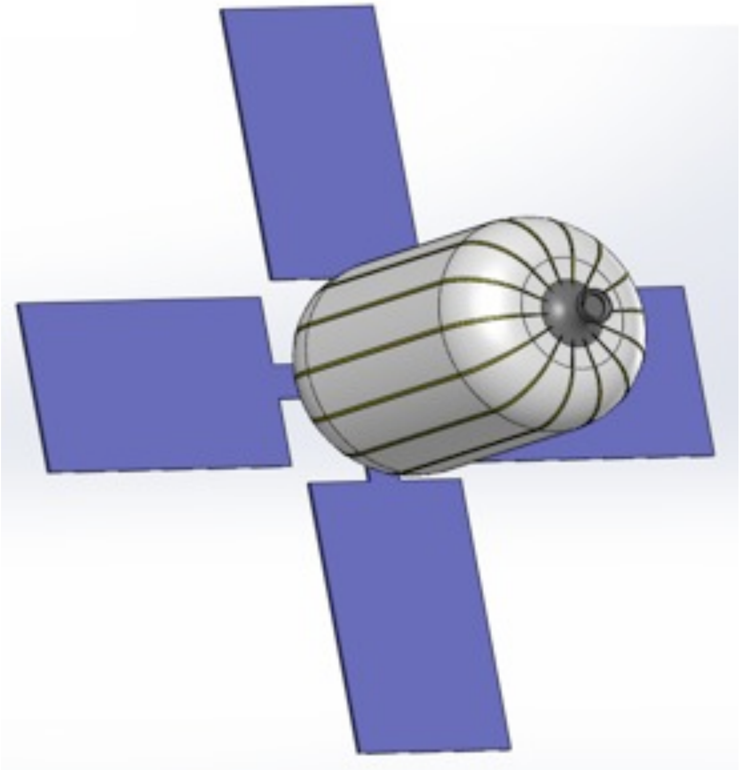


Spacecraft Design & Layout

Vehicle Stack

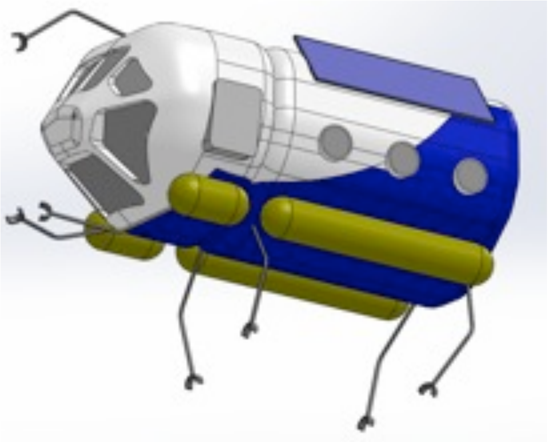


Crewed Vehicles



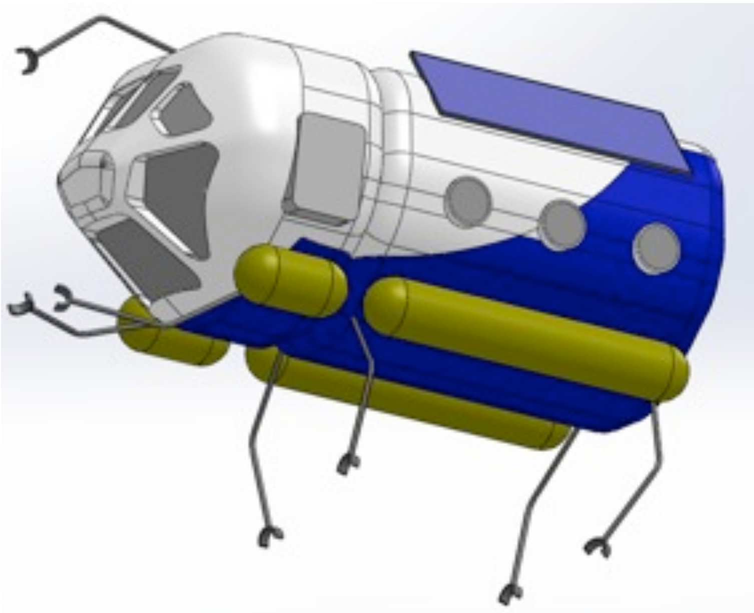
Bigelow DSH

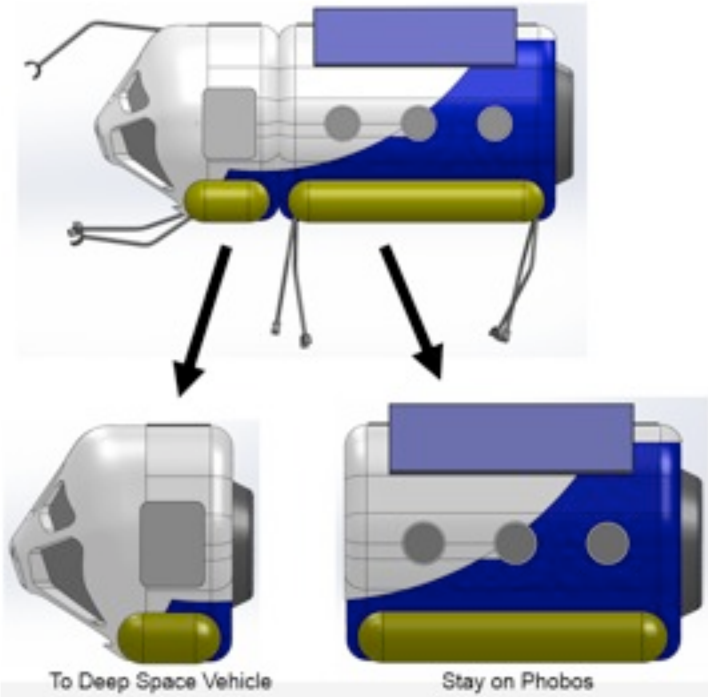
Dragon CV



PSE

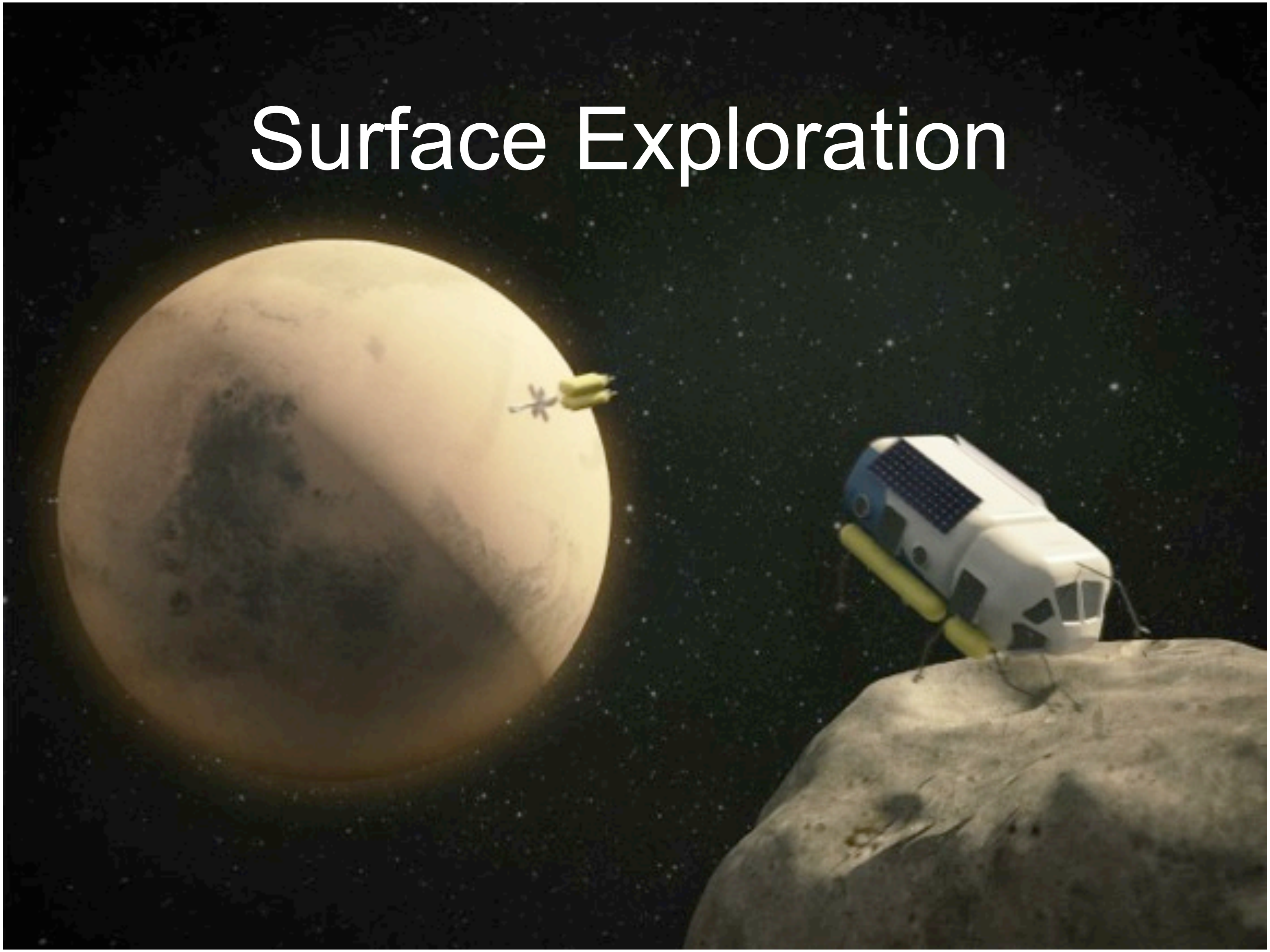
PSE - Phobos Surface Explorer

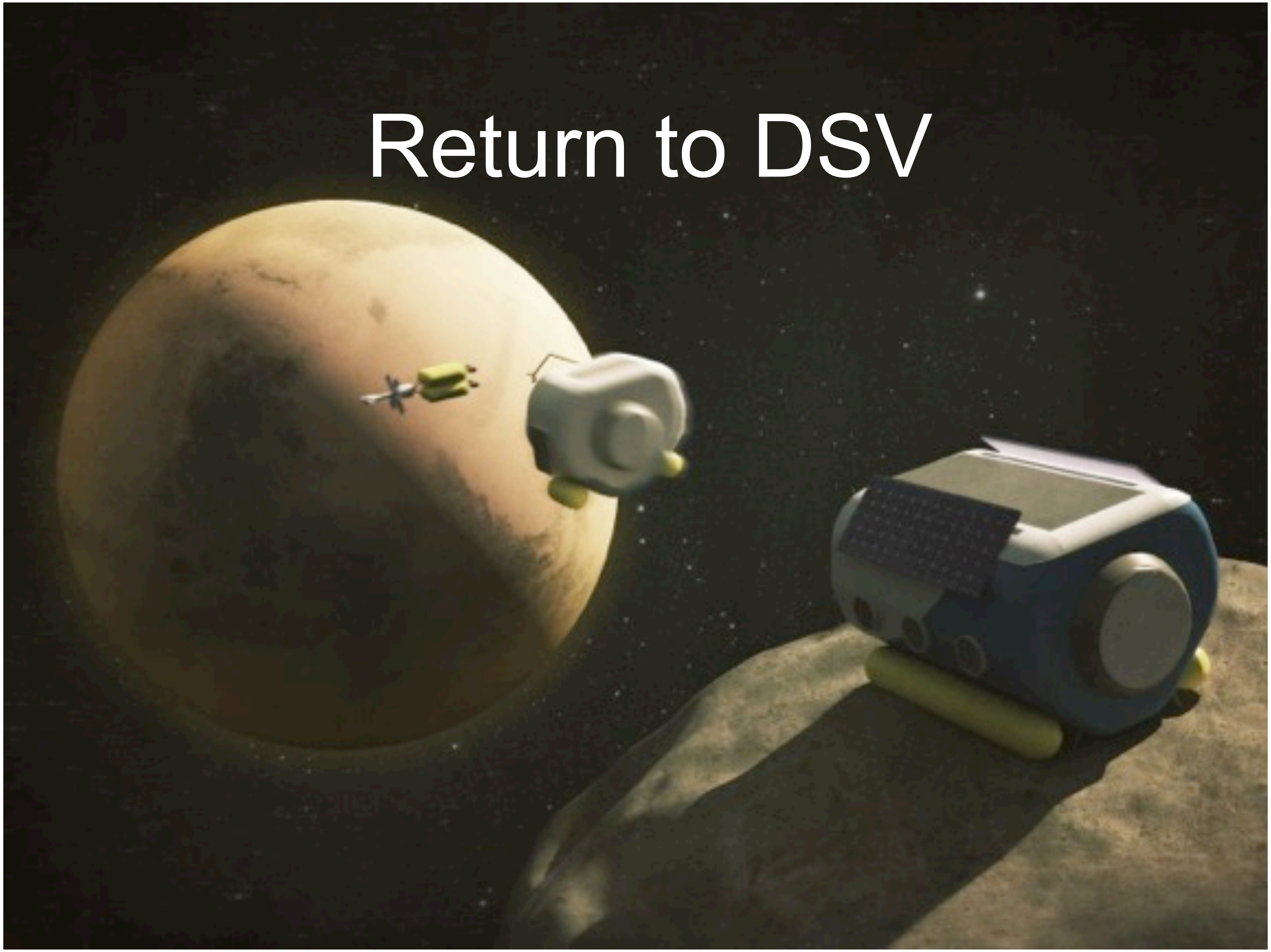




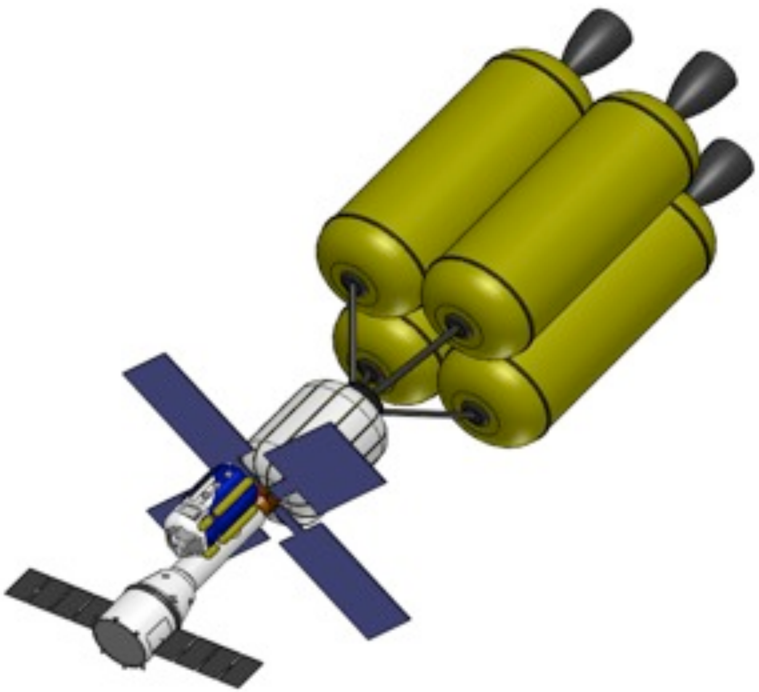
PSEP **PSE Habitat**

- 2-Stage SEV - Habitable and Ascent
- Wet mass = ~17000 Kg
- Science Instruments = ~1000 Kg


Surface Exploration


Return to DSV

Propulsion Systems and Launch Capability Requirements



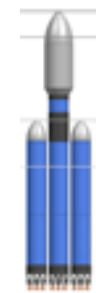
Launch Vehicle Choices

Falcon 9 (1)

- Crew Vehicle (10,100 kg)
- 10,450 kg to LEO
- Cost: $130-140M

Falcon 9 Heavy (1)

- DSH & PSE (17,000 kg)
- Cost: $80-125M



SLS (4)

- NTR Tanks and System
  - (246,000 kg over4 launches)
- Cost: $2.5 billion

Mass Budget For Propulsion System Design

		DSH (Outbound)	CV (Outbound)	PSE	PSEP (Ascent)	DSH (Inbound)	CV (Inbound)
Component	**Notes**						
ECLSS	Food, Gases for Life Support, Water, Tanks, Life Support Hardware	8		2		8	
Med	Centrifuge, Countermeasure, Excersice, Clinical medicine, rapid prototyper, small fridge	1				1	
Crew	Astronauts, clothes	0.6	0.6	0.3	0.3	0.6	0.6
Habitat Structure	Beds, Storage, equipment, structure	10				10	
Wet Mass	Avionics, Power, Environment Protection, Crew systems	6				6	
Science Equipment	Science Equipment for Crew to use to/from Phobos	0.2		1		0.2	
Propulsion System	Engine, Tanks, Propellant	184		3.7	0.9	75.4	
Dragon Capsule			9.5				9.5
Samples	Samples from Phobos				0.5		0.5
Remote Sensing				0.07			
PSE - Hab				6			
PSEP Total				3.7			
PSEP Structure					2		
Total:		**209.8**	**10.1**	**13.07**	**3.7**	**101.2**	**10.6**

4 SLS Launches ~46 tons H_2 each
Falcon Heavy ~39 tons
Falcon 9 ~10.1 tons

Units: Metric Tons

Propulsion Trade Study (1/2)

Propulsion systems considered:

- Chemical Propulsion: LOX/H2, LOX/CH4, N204/MMH [Humble, 1995]
- Electric Propulsion: Clusters of 50 kW Hall Thrusters [Strange et al., 2011]
- Nuclear Propulsion: NERVA Variant, Particle Bed Reactors [Humble, 1995]

Considered Multiple Flight and Rendezvous Scenarios, examples to follow

Propulsion Trade Study (2/2)

	Description	IMLEO (Metric tons)	Crew Time of Flight (days)
LEO Rendezvous	a.) NTR DSV departure from LEO	279	456
	b.) Cluster of fourteen 50 kW Hall thrusters DSV departure from LEO	202	1076
HEO Rendezvous	a.) A NTR DSV is placed in HEO by cluster of six 50 kW Hall thrusters which rendezvous with CV and then departs	297	456
Cargo Rendezvous with DSV at Phobos	a.) Cargo pre-placement at Phobos by cluster of six 50 kW Hall thrusters and DSV departure with NTR	276	456
Cargo and Fuel Rendezvous with DSV at Phobos	a.) Cargo and fuel pre-placement at Phobos by cluster of six 50 kW Hall thrusters and DSV departure with NTR	248	456

Chosen:

- **LEO Rendezvous with Nuclear Thermal Propulsion**

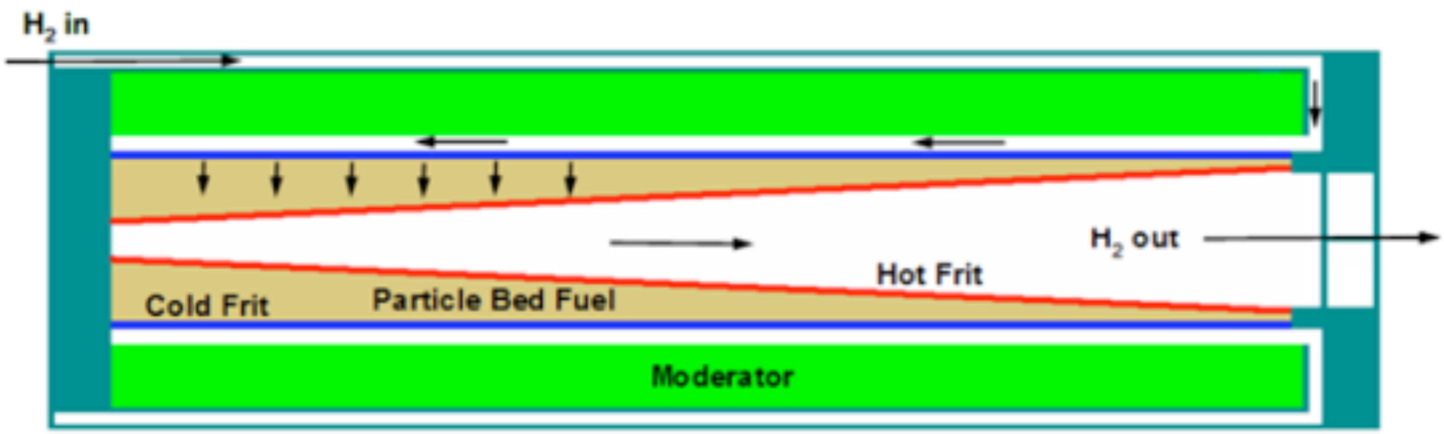
Reasoning:

- Time constraints of opposition class mission limit efficiency improvements of EP
- Small mass of total system which is not necessary for DSV flight (human flight) ⟶ limits efficiency improvements of
- Risks of fuel pre-placement outweigh by performance improvements

DSV Propulsion Stage

- Assumptions:
  - Zero-boil off for cryogens
  - Sufficient PBR technology
- NTR Particle Bed Reactor type
  - Chosen for high thrust/weight ratio

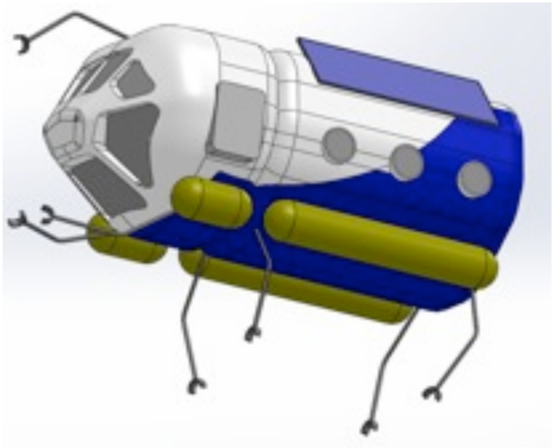
Thrust (N)	ISP (sec)	Engine Dry Mass (tons)	Propellant Mass (tons)	Propellant Tank Mass (tons)	Propellant Tank Volume (m^3)
333000	900	3.925	235.4	10	3440



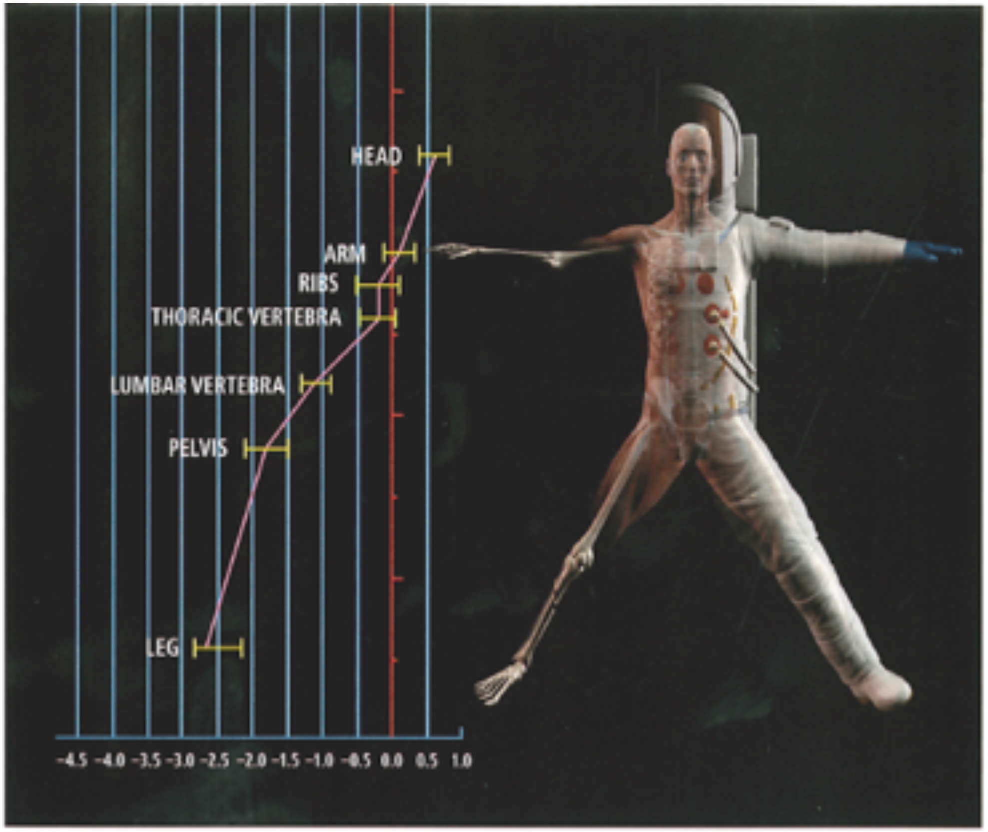
[Emrich, 2013]

PSE Propulsion Stage

- PSE Descent Engine:
  - LOX/Methane type engine for technology demonstration
  - Small RCS thrusters
  - ISP: 380 sec
- PSEP Engine:
  - N2O4/MMH
  - Reliability and ability to escape Phobos and explore the terrain
  - Based off Draco thrusters
  - ISP: 320 sec



Human Factors



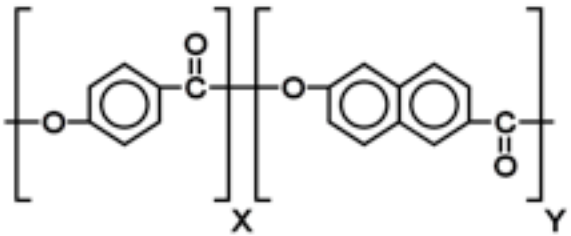
Crew Selection

- Optimal Size of Crew
  - 4 astronauts, in their 40s, mixed gender
  - Roles: Chief commander, Geologist, Engineer, Flight Surgeon
- Physiological Testing
- Psychological Testing
  - Psychiatric Diagnostic & Statistical Manual IV
  - Neuroasthenia
- Genetic Testing
  - HRAD9 Gene - Increased Radiation Tolerance
  - Screened for future diseases
- Final Selection
  - Field Tests
  - Self-evaluation

[Seedhouse, 2012]
[Pandita, 2006]

Radiation Mitigation

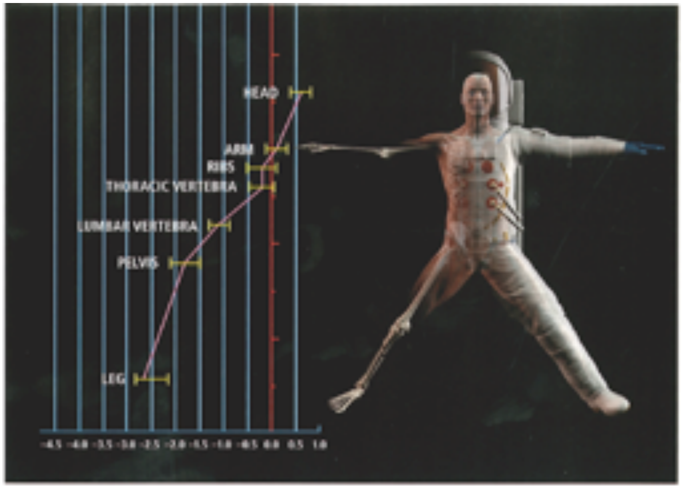
- Dose shall not exceed 3% excess cancer mortality risk
- Assumptions:
  - Safe Haven
  - Shield sleeping quarters; water blanket
  - Five Dosimeter Monitor
- Vectran Material
  - Design thickness to 20 [g/cm^2]
- Passive and Active Shielding
- Future Technology Demonstration
  - Photobioreactor used for algae recycled biomass



[Turner, 2013] [Atwell, 2005]

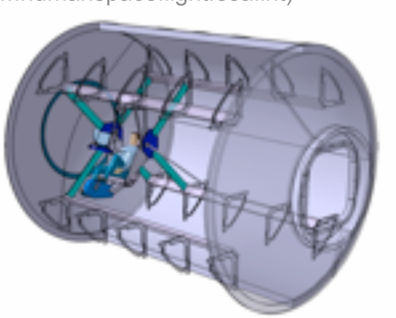
Physiology in space

- Physiological deconditioning:
  - Bone loss
  - Muscle atrophy
  - Cardiovascular adaptation
  - Motion sickness

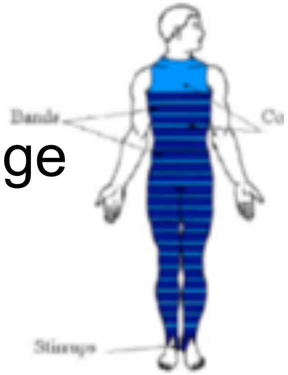


(Vico, www.humanspaceflight.esa.int)

- Countermeasures:
  - Exercise: aerobic vs. resistance
  - Artificial gravity: short radius centrifuge
  - IVA wearable concepts:
    - Exoskeleton
    - Gravity Loading Countermeasure Suit



(ESA , 2011)



(Waldie, 2011)

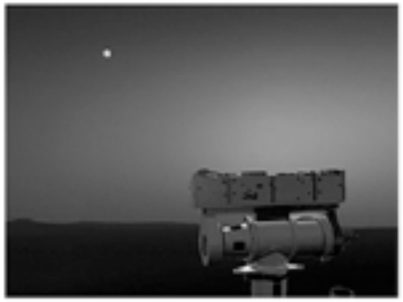
Clinical Medicine

- Advanced Research in Space Medicine I & II
  - Highest risk and incidence
    - Medical Packs
    - Extend shelf life
- Telemedicine
  - Tablet technology
  - Self-diagnosis
- 3D Metal Printing
  - Aluminum wrappers
- Surgical Suite
  - Inflatable sterile environment
  - Magnetic tray
  - Laminar flow

[Comet, 2003]
[Barrat, 2008]

Psychological Considerations

- Crew Selection
- Interpersonal Conflicts
  - Training on conflict resolution
- Sleep Deprivation
  - Medication
- Boredom
  - Tablet Technology: Reading, video games, and skill training
  - Outreach activities and science experiments
- Group Compatibility
  - Common Meal
- Pale Blue Dot Syndrome
  - Family Communication
  - Virtual Reality



[Clement, 2005]
[Pandita, 2006]

ECLSS

AIR

- CO_2 Removal:
  - 2 Electrochemical Depolarized Concentrator (EDC)
- O_2 Generation:
  - 3 Static Feed Water Electrolysis (SFWE)
  - 3 kg/day per unit
- 2 Trace Contaminant Control (TCC)
- Heat Exchangers (CHX)

WATER

- Regeneration by 2 VPCAR units
  - Waste water into potable water
  - 250 kg/day per unit
- Air Evaporator System (AES)
  - Recover residual H_2O

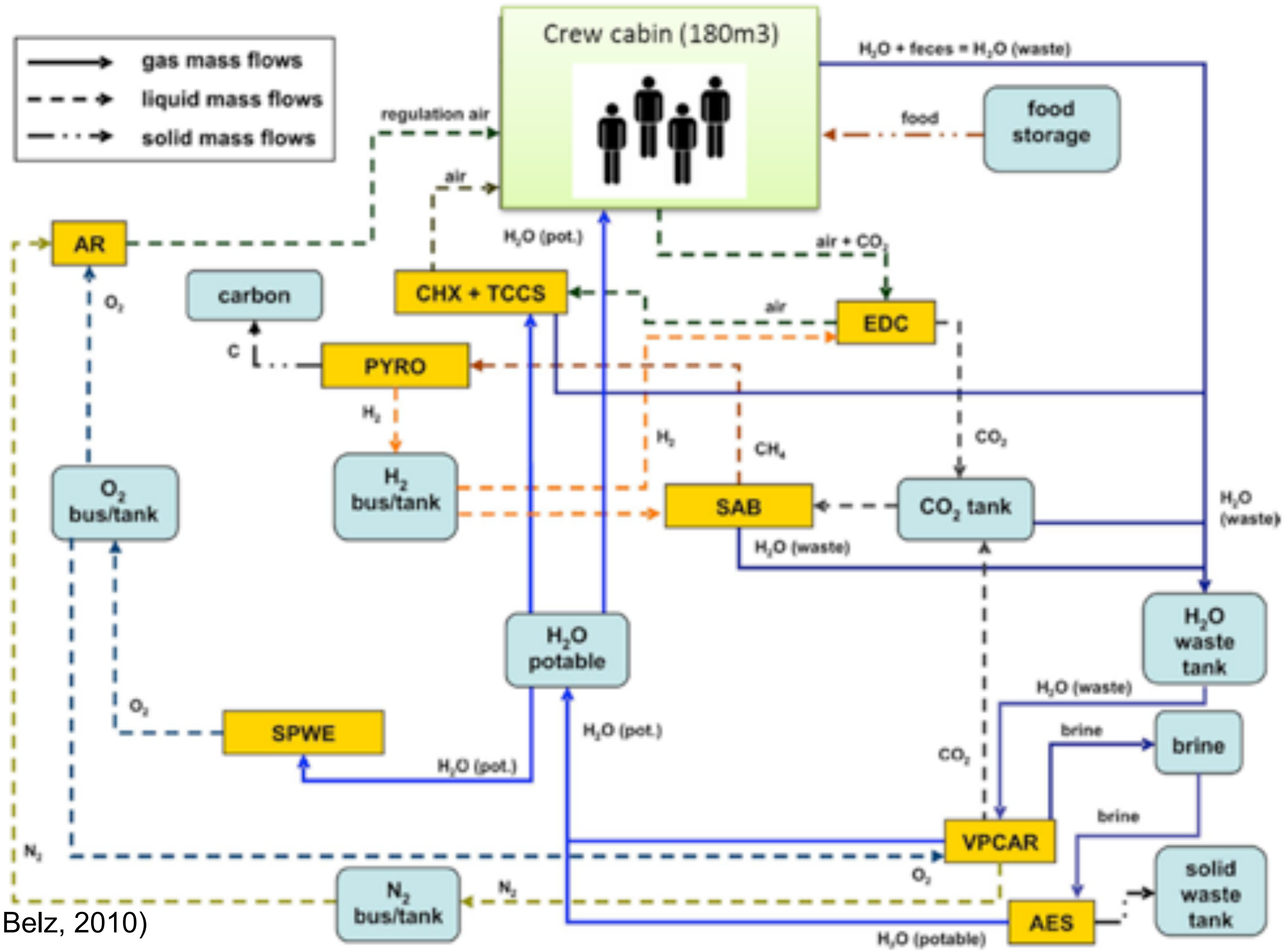
FOOD

- 1200 kg of dehydrated food
  - Maximum intake per person = 0.56 kg/d

WASTE MANAGEMENT

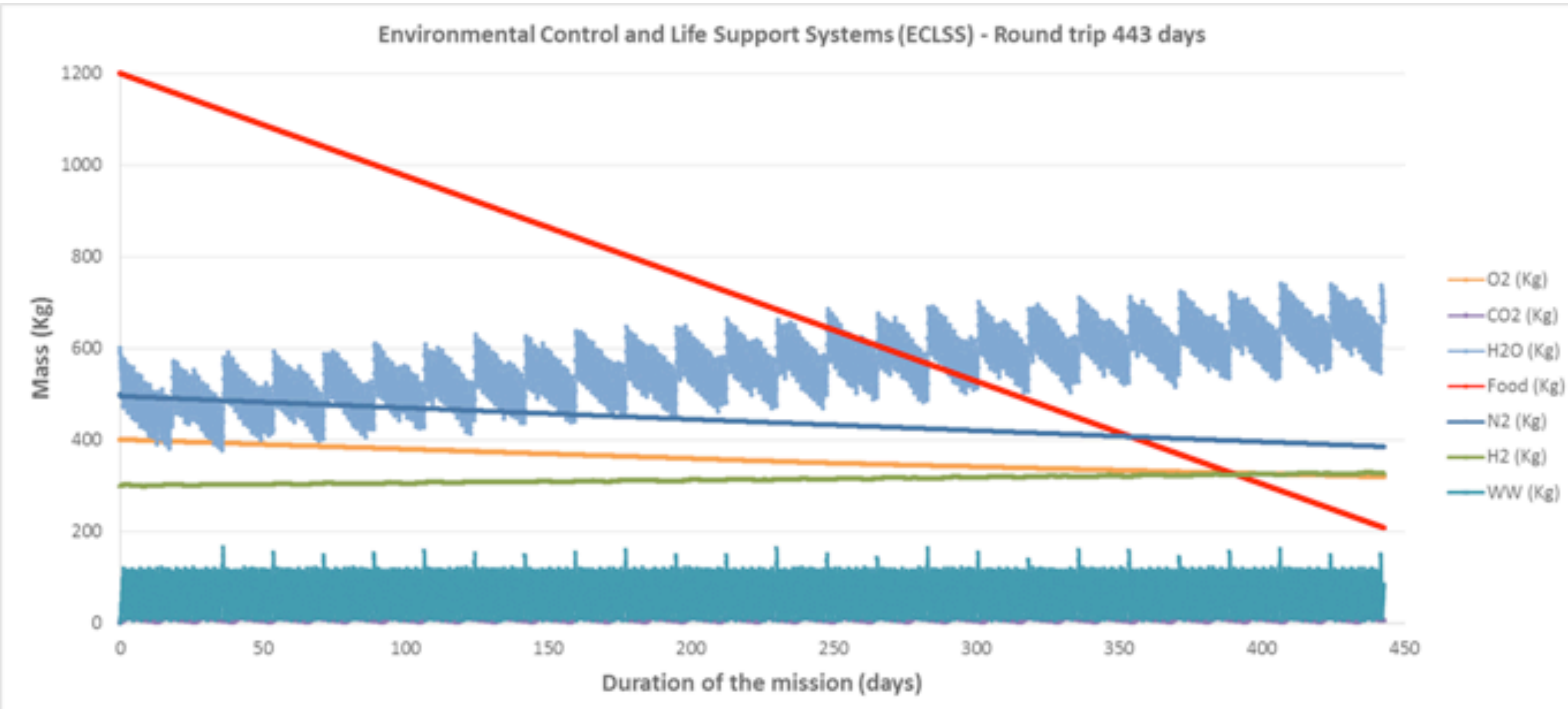
- CO_2 Reduction: 2 Sabatier Reactors
  - $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
- CH_4 Reduction: 2 Pyrolysis units
  - CH_4 into C and H_2

ECLSS Architecture

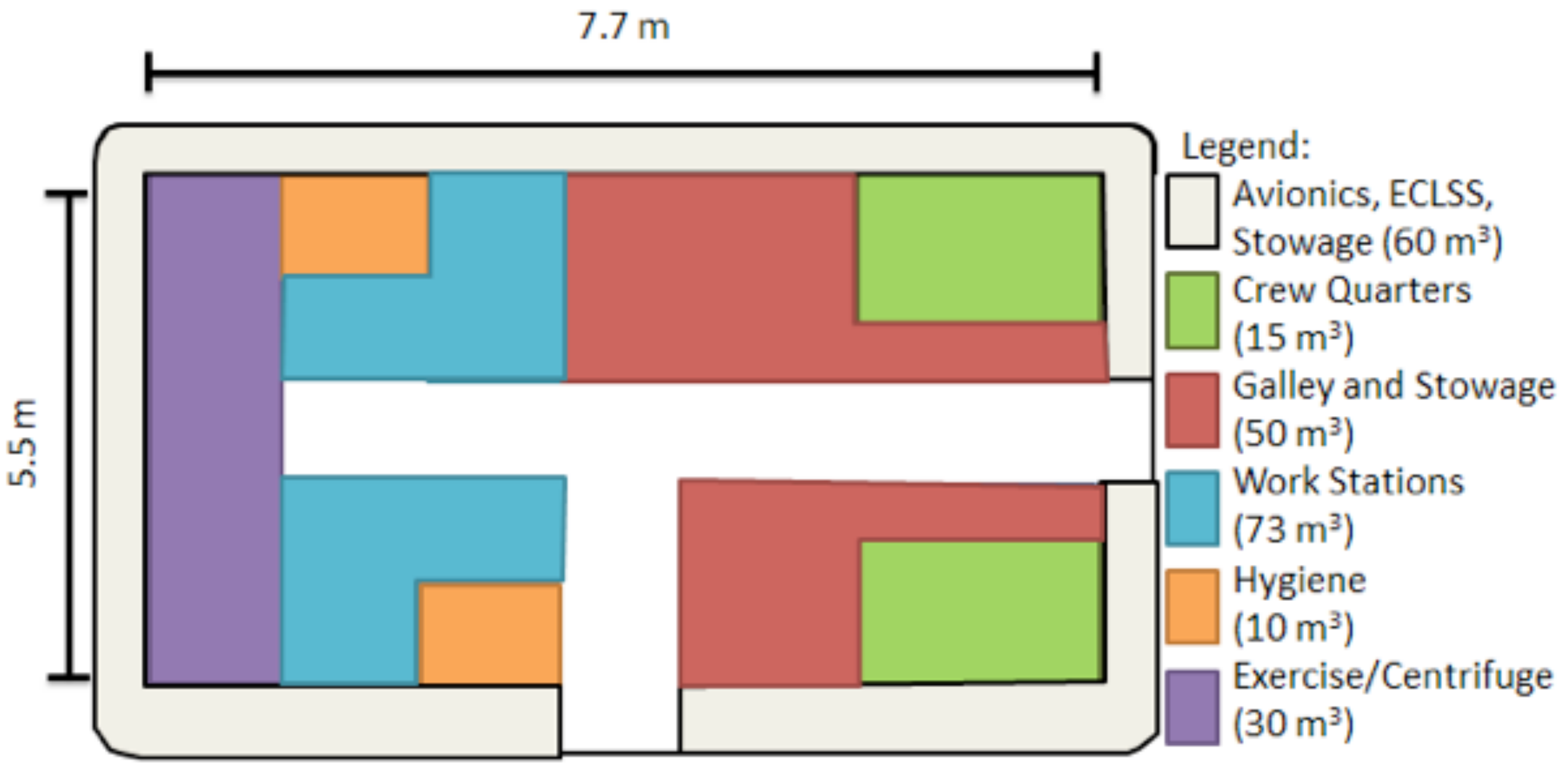


(Image modified from Belz, 2010)

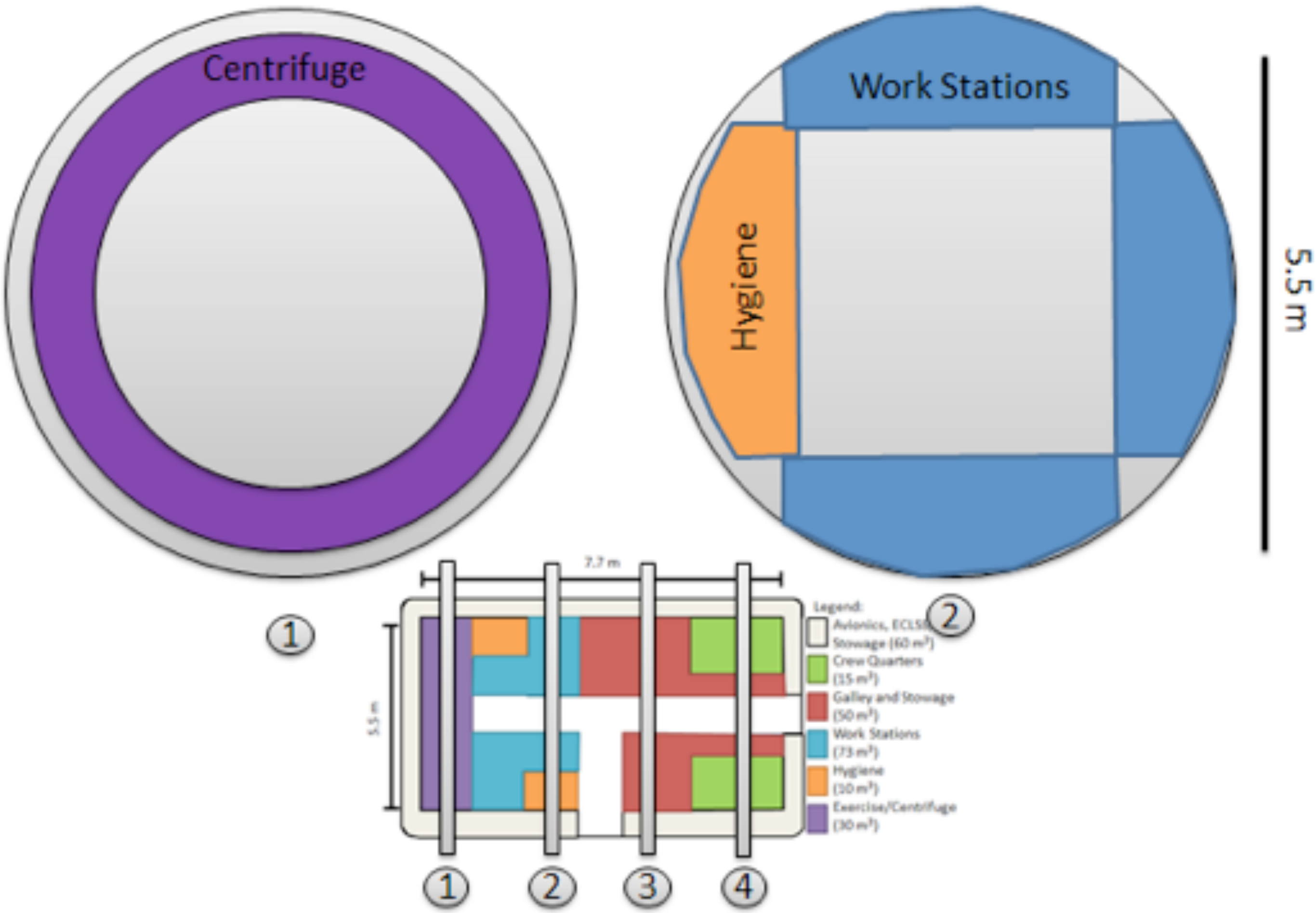
Deep Space Habitat ECLSS



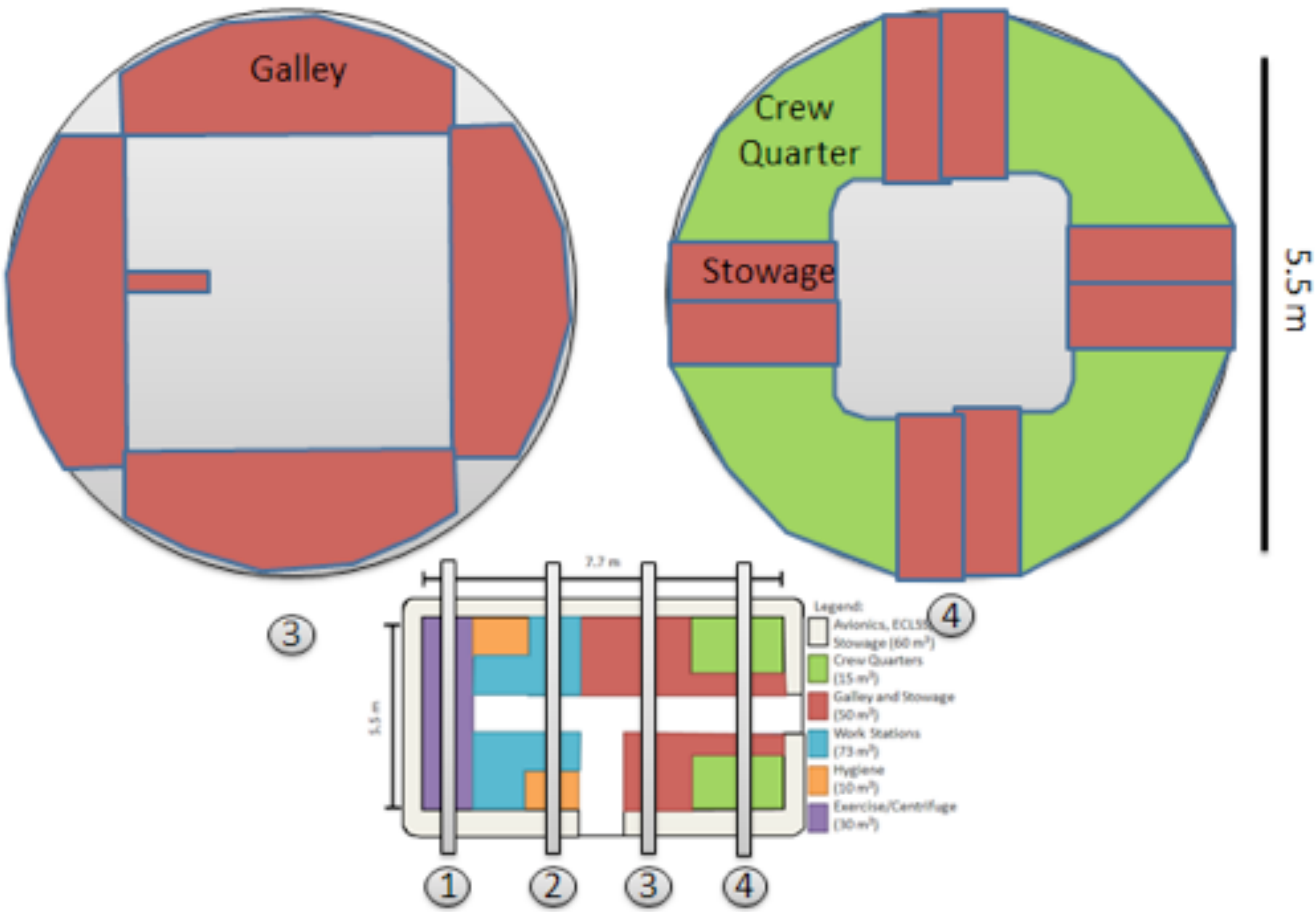
Habitability



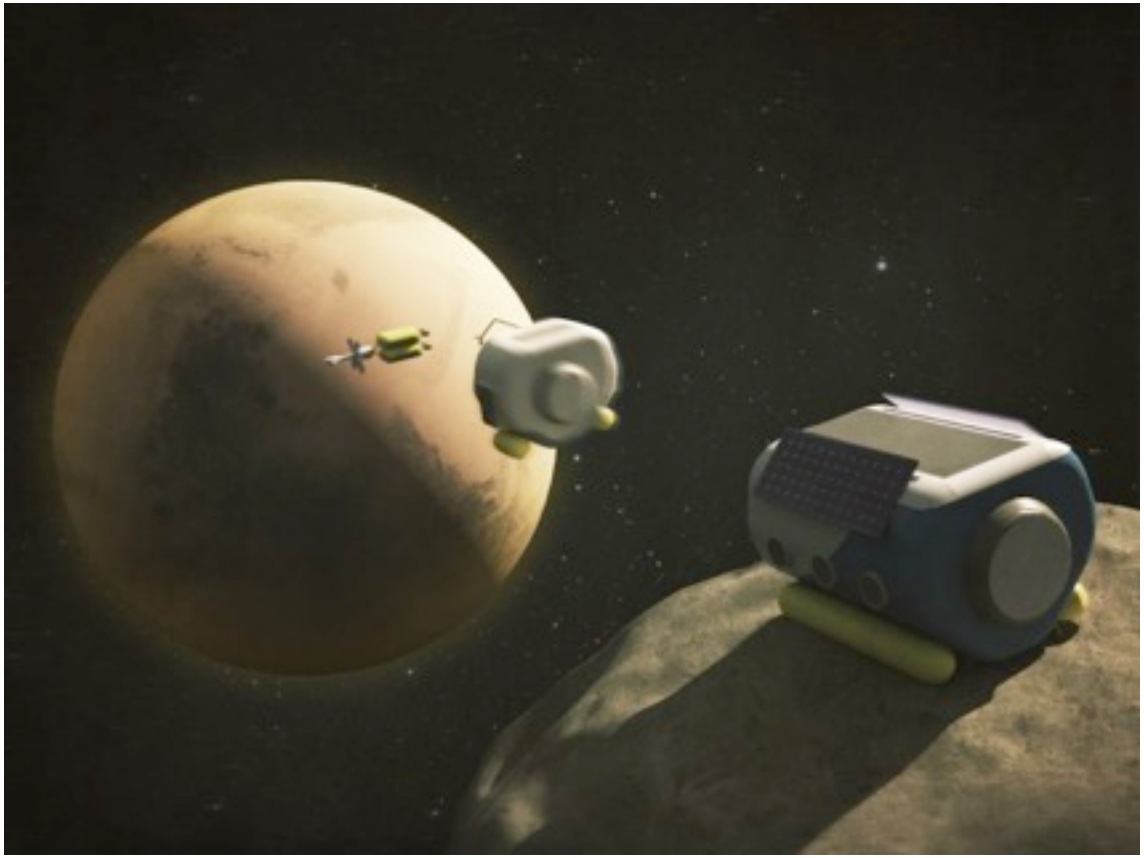
Habitability



Habitability

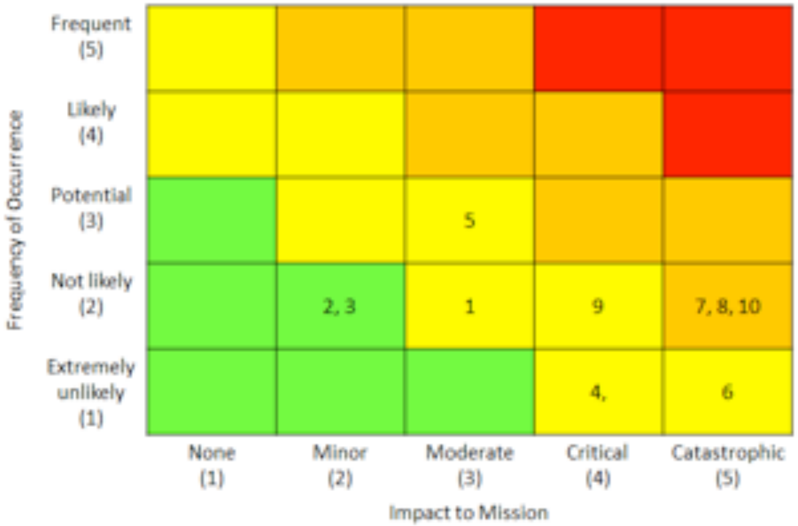


Conclusion



Conclusions

- Our approach:
  - Stepping stone to Mars
  - Global context
- Risks are high for Mars missions
- ...but gains are greater
- (So long as the gains are well-communicated)



System Risk Assessment

Ending Quote

"Ever since there have been people, there have been ***explorers****, looking in places where other hadn't been before. Not everyone does it, but we are part of a species where some members of the species do—to the benefit of us all."*
-Neil de Grasse Tyson

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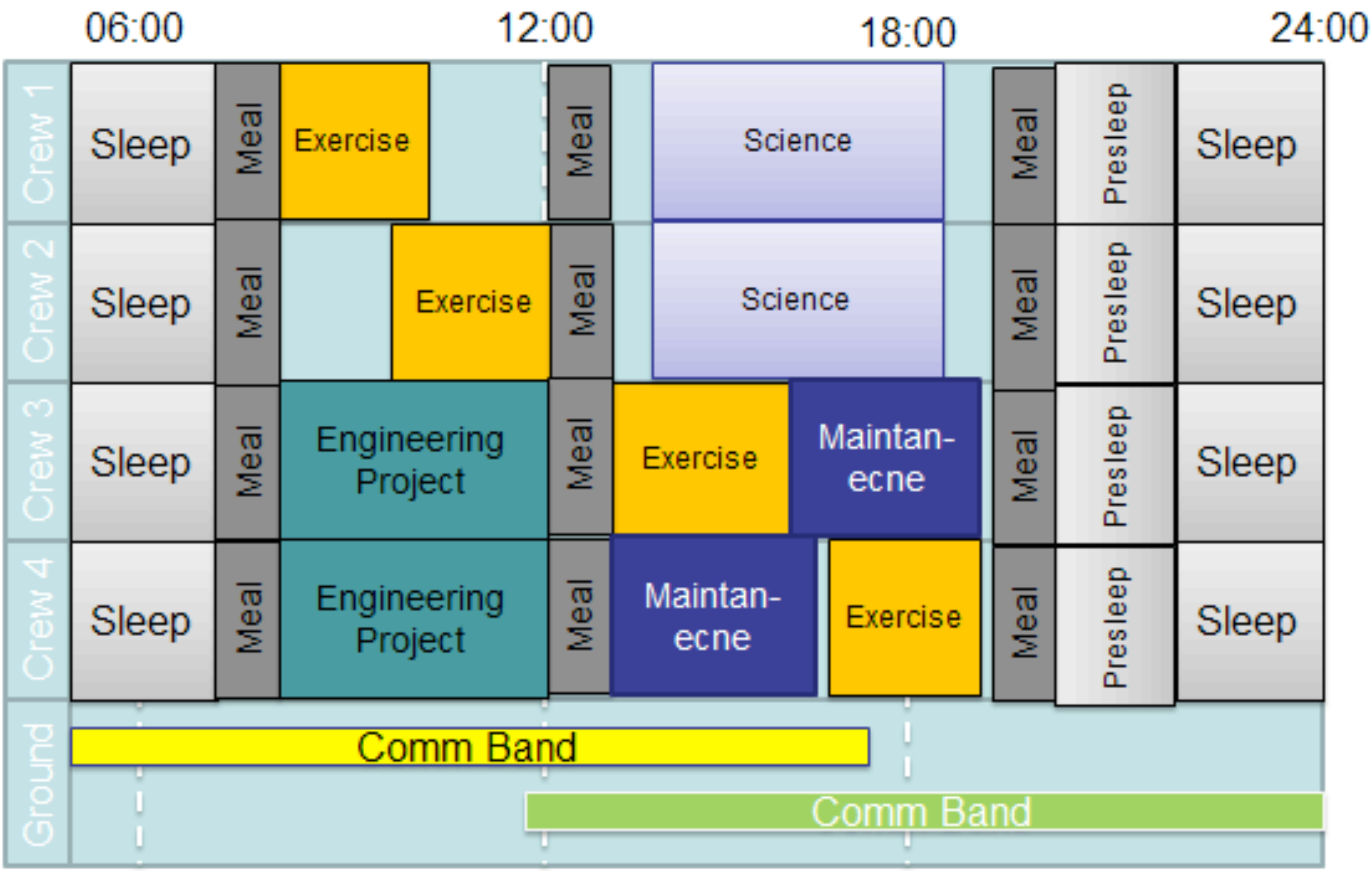
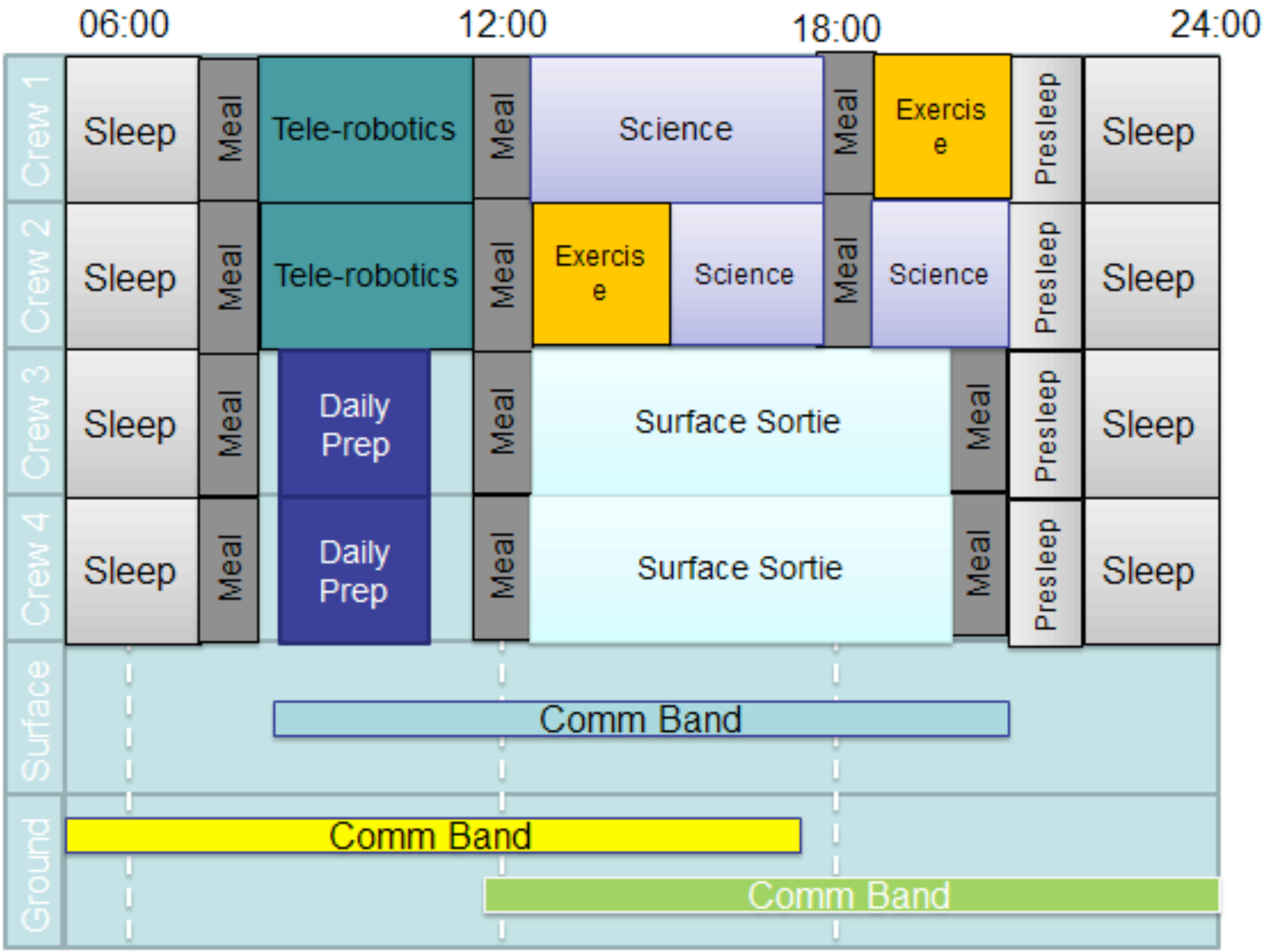
Dr. Louis J. Alpinieri
Dr. Hideo Ikawa
Mr. John K. Wimpress
John and Joy Caldwell, Caldwell Vineyard

Backup Slides

Example of Inbound/Outbound Daily Activities Crew Timeline

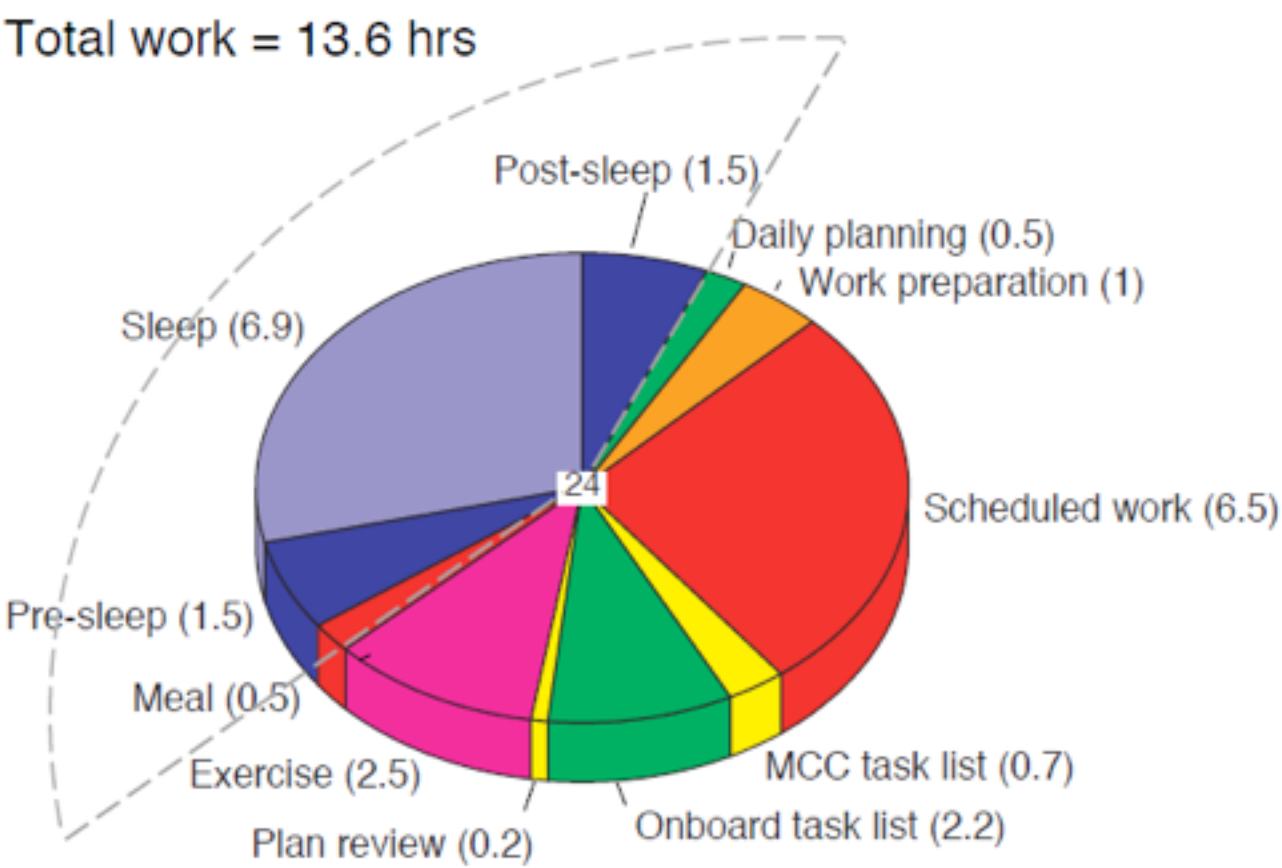


Surface Ops


06:00
12:00
18:00
24:00
Crew 1
Sleep
Meal
Tele-robotics
Meal
Science
Meal
Exercis e
Presleep
Sleep
Crew 2
Sleep
Meal
Tele-robotics
Meal
Exercis e
Science
Meal
Science
Presleep
Sleep
Crew 3
Sleep
Meal
Daily Prep
Meal
Surface Sortie
Meal
Presleep
Sleep
Crew 4
Sleep
Meal
Daily Prep
Meal
Surface Sortie
Meal
Presleep
Sleep
Surface
Comm Band
Ground
Comm Band
Comm Band

Habitability

	Volume [m³]	Qty.	Subtotal [m³]
Crew Quarters	5	4	20
Galley, Locker Access, Operations	50	1	50
Science workstations	35	2	70
Hygiene and waste management	5	2	10
Centrifuge/exercise	30	1	30
Translation paths	2.5	3	7.5
Total Volume	180		



[Clement, 2012]

#	Item	Risk and Mitigation Strategy	Impact	Prob.	Risk
1	Risk	Loss of sample containment	3	2	6
	Strategy	System redundancy / multiple samples			
2	Risk	Phobots miss	2	2	4
	Strategy	Ensuring criteria for release			
3	Risk	Rover mobility failure	2	2	4
	Strategy	Robotic exploration capabilities			
4	Risk	Imperfect trajectory maneuvers	4	1	4
	Strategy	Ensuring sufficient margin in course planning			
5	Risk	Radiation and microgravity impacts on crew (chronic)	3	3	9
	Strategy	Shielding and countermeasures			
6	Risk	ECLSS failure	5	1	5
	Strategy	Redundancy			
7	Risk	Decompression sickness / EVA failures	5	2	10
	Strategy	Proper EVA protocol			
8	Risk	Medical emergencies	5	2	10
	Strategy	Crew training, medical supplies, and surgical suite			
9	Risk	Failed in space rendezvous (Earth proximity)	4	2	8
	Strategy	Abort capabilities to earth			
10	Risk	Structural failure of crew habitat	5	2	10
	Strategy	Prior demonstration of technology and testing			

	1	2	3	4	5
Impact on Mission	None	Minor	Moderate	Critical	Catastrophic
	No impact, No fix required	Minor impact, Fix required	Moderate impact, Fix required	Loss of Mission Objective	Loss of Vehicle or Crew Member
Probability of Occurrence	Extremely Unlikely	Seldom / Not Likely	Occasional / Potential	Likely	Frequent

Risk Matrix

Frequency of Occurrence

	None (1)	Minor (2)	Moderate (3)	Critical (4)	Catastrophic (5)
Frequent (5)					
Likely (4)					
Potential (3)			5		
Not likely (2)		2, 3	1	9	7, 8, 10
Extremely unlikely (1)				4,	6

Impact to Mission