Lunar and Mars Mission Analysis and Design Using Commercial Launch Systems and the International Space Station

ARCH 7610: Master's Project – Space Architecture
ARCH 6398: Special Projects

David Smitherman
Sasakawa International Center for Space Architecture
University of Houston, Houston, TX

Summer Semester 2008
August 12, 2008

Course Objectives

- ARCH 6398: Special Projects
  - Detailed Spreadsheet analysis for sizing of launch vehicles, lunar test mission vehicles and systems, Mars mission vehicles and systems, and program planning
- ARCH 7610: Master's Project – Space Architecture
  - Mission concept to promote economic growth and infrastructure development in space, at the moon, and Mars
  - Emphasis on using existing and near-term space systems and technologies
  - Design development of compatible Lunar and Mars architectures
  - Design studies using 3D computer modeling, animations, and computer generated plastic models

Presentation Contents

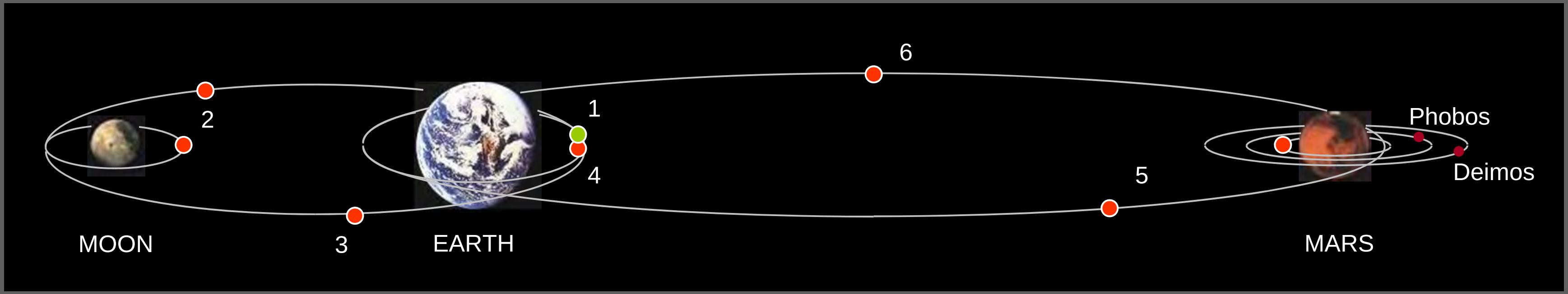
Lunar and Mars Mission Scenario

Following the completion of the International Space Station (ISS) mission, the International Partners agree to pursue human exploration missions to Mars that include a development path for commercial space development and lunar exploration. The missions will provide for continued exploration and development in space through the utilization of in-situ resources and support for the expansion of commercial operations and enterprises.

Lunar and Mars Mission Concept

A Mars Ship is developed at the ISS in increments over 8 to 10 years as the ISS has been developed. It then flies a test mission to the Moon before being refurbished for a mission to Mars. The mission scenario includes:

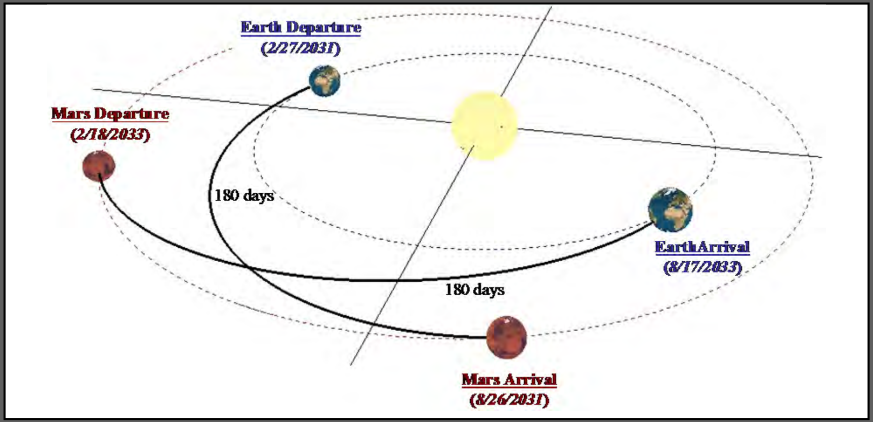
1. Build Mars Ship attached to the ISS.
2. Launch Mars Ship to the Moon to test all systems and mission operations.
3. Return Mars Ship to Earth orbit.
4. Rebuild or refurbish the Mars Ship for the mission to Mars.
5. Launch Mars Ship to Mars and conduct full operational mission.
6. Return Mars Ship to Earth orbit and refurbish for next mission.



Lunar and Mars Mission Profiles

Mars Mission Profile

- Earth to Mars transfer time of 6 months, and surface time of 18 months
- Propellant production depot established in Mars orbit and on surface to service reusable Landers and return vehicles
- Total mission = 30 months or 900 days



Lunar Test Mission Profile

- Earth to Luna transfer time of 6 months, and surface time of 18 months to duplicate Mars mission operations
- Propellant storage depot established in lunar orbit to service reusable Landers
- Total mission = 30 months or 900 days

Luna Transient time options

- 6 month Lunar Orbit stay
- 6 month elliptical orbit around the Earth & moon

Mars Science and Exploration Objectives

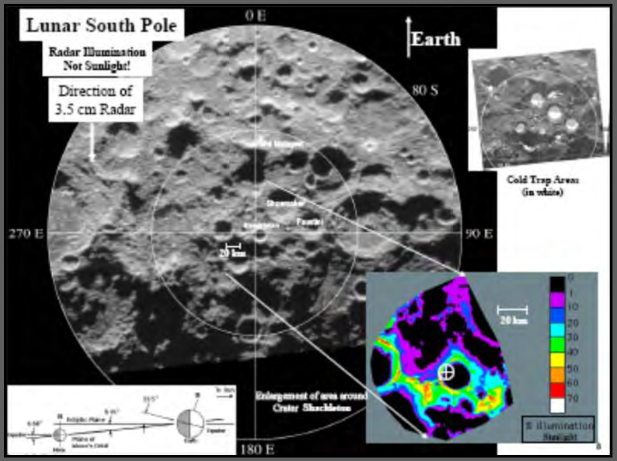
- Transport a human exploration crew to Mars and its' two moons, Phobos and Deimos, and return them safely to Earth
- Search for aqueous environments and for signs of past and present life
- Increase our knowledge about the solar system's origin and history
- Return selected samples of Martian material to Earth for detailed analysis

Mars today.

Mars as it may have looked when water was on the surface.

Lunar Science and Exploration Objectives

- Conduct a full scale Mars mission simulation to test systems and operations
- Land a human crew on the moon and return them safely to Earth
- Search for life forms and unique resources in the permanently shadowed craters at the poles
- Return samples of lunar water-ice and other resources to Earth for detailed analysis



International Partnership Objectives

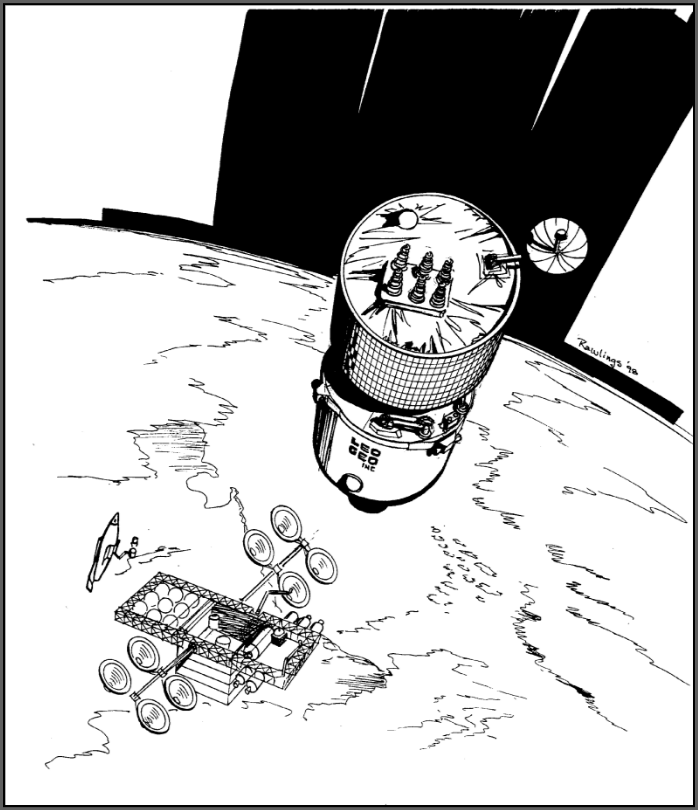
- Explore the feasibility of sustaining human expansion into space utilizing space resources from the Moon, Mars, Martian Moons and Near Earth Asteroids
  - Continue and strengthen cooperation between the International Space Station partners and expand the Partnership to include other interested Nations
  - Utilize commercial resources and operations to the greatest extent possible
  - Support the development of new space enterprises by establishing needed infrastructures and removing the risk involved with new ventures
  - Create a tax infrastructure that funnels tax revenues from profitable space ventures into the development of new space enterprises and space launch infrastructures

Commercial Objectives

- Develop an economically viable and self-sustaining space-based economy
  - Develop an in-space propellant refueling and servicing capability to support earth orbit satellite systems and new explorations systems
  - Support the development of a transportation infrastructure that will make it possible to return resources from the Moon, Mars and asteroids for exploration and profit
  - Extract oxygen from the moon and confirm the existence of water-ice resources at the moon and Mars to support exploration and commercial development
  - Begin construction of an infrastructure for permanent human settlements in space, on the Moon, and on Mars

Satellite Servicing

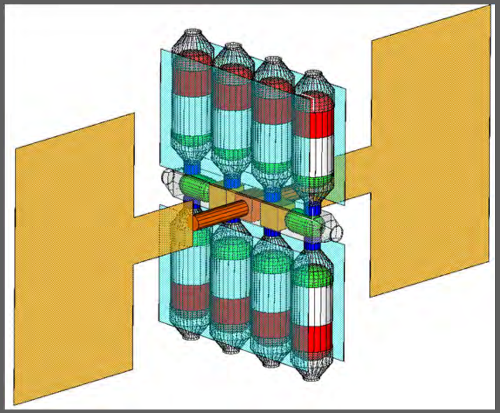
- The satellite servicing industry capabilities would include:
  - Ability to capture and relocate existing satellites and debris
  - Refueling of new serviceable satellites
  - Storage of cryogenic oxygen and hydrogen propellants at a servicing platform on orbit
  - Satellite servicing and replacement of parts on orbit via remote operations or crew operations from an advanced crew transfer vehicle
- The new satellite servicing systems would be utilized to construct and maintain the new Mars Ship and prolong the operations of the International Space Station.



Transfer vehicle launched from a servicing platform.

Propellant Production and Storage

- Propellant production and storage would support the satellite servicing industry and would include:
  - Long-term storage of cryogenic hydrogen and oxygen propellants
  - Accumulation of water and conversion to propellants for space systems and future Lunar and Mars missions
  - Development of a propellant production system for use on the surface of Mars and in Mars orbit



Propellant production depot.

Propellant storage depot.

Asteroid Exploration and Mining

- Asteroid exploration and mining capabilities would include:
  - Crew transfer vehicle to the moons of Mars and other asteroid-like bodies
  - Extraction and return of asteroid materials
  - Processing of asteroid materials on orbit to support commercial and exploration systems
  - Asteroid orbit manipulation for mining and defense

Asteroid mining could support other industries and exploration goals

Asteroid defense is needed

All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

Space Tourism

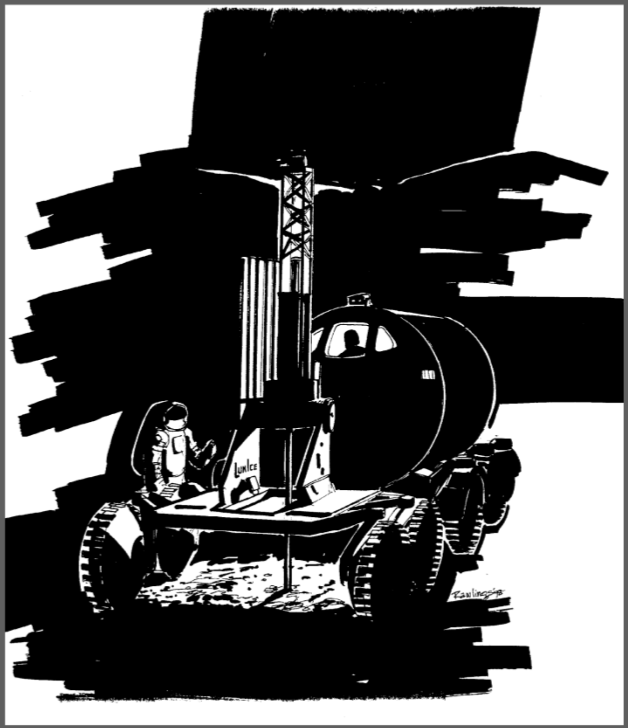
- Space tourism capabilities include:
  - Development of commercial passenger launch systems for suborbital, orbital, and lunar orbit tours
  - Development of commercial space stations and space hotels as commercial research facilities and tourist destinations
  - New industries supporting entertainment such as 0-g televised sporting events and 0-g movie production stages
  - Objective is to build the infrastructure that will support development of large permanent settlements in space on the Moon and Mars

Space hotel and multiuse facility.

Tourism out to the moon and back.

Lunar and Mars Exploration and Development

- Lunar and Mars exploration and development capabilities include:
  - Crew transfer vehicle to the surface of the Moon and Mars
  - Extraction and return of surface and subsurface materials
  - Processing of materials on the surface to support commercial and exploration systems
  - Return resources from the Moon and Mars for a profit



Surface and subsurface exploration will be done at the Moon and Mars to extract resources, and to test operational concepts human exploration and settlement

Crew Launch Systems

- Crew launch systems include the existing Russian Soyuz vehicle, and the US Ares I vehicle now under development. The Space Shuttle is assumed to be no longer available.
- Soyuz
  - 3 crew capacity to ISS
  - Return capsule
  - Expendable
  - 7,000-8,000 kg to LEO
  - Payload Fairing (dia. x ht.)
    - Outside: 3m x 9m
- Ares I (Under Development)
  - 6 crew capacity to ISS
  - Return capsule
  - Expendable
  - Payload Fairing
    - Outside: 5m diameter capsule

Russia's Soyuz Launch Vehicle

United States' Ares I Vehicle (under development)

All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

Cargo Launch Systems

Cargo launch systems include existing systems plus additional expansion of the Delta IV vehicle to include the author's version of a new Delta V vehicle

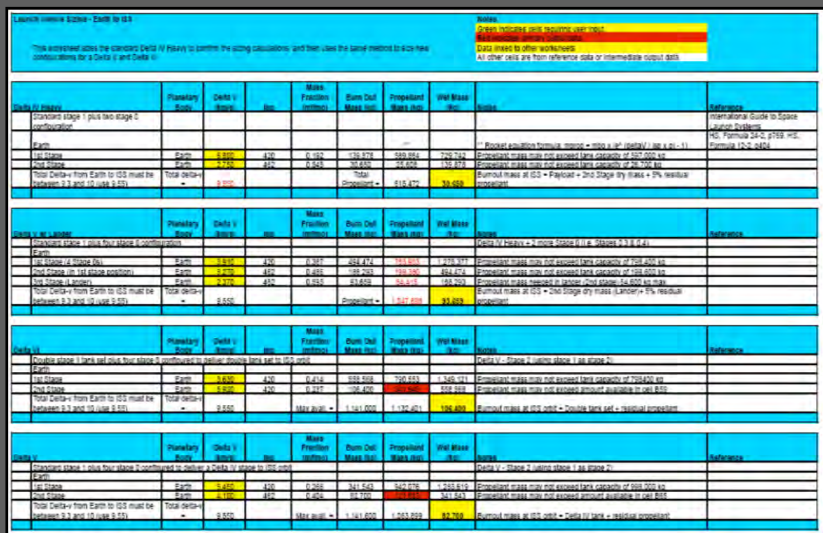
- Delta IV Heavy
  - 25,000 kg to LEO
  - Payload Fairing
    - Outside: 5.1m x 23m
    - Inside: 4.572m x 14.884m
- Proton M
  - 21,000 kg to LEO
  - Payload Fairing
    - Outside: 4.1m x 15m
    - Inside:
- Ariane 5
  - 18,000 kg to LEO
  - Payload Fairing
    - Outside: 5.4m x 17m
    - Inside: 4.570m x 10.350m

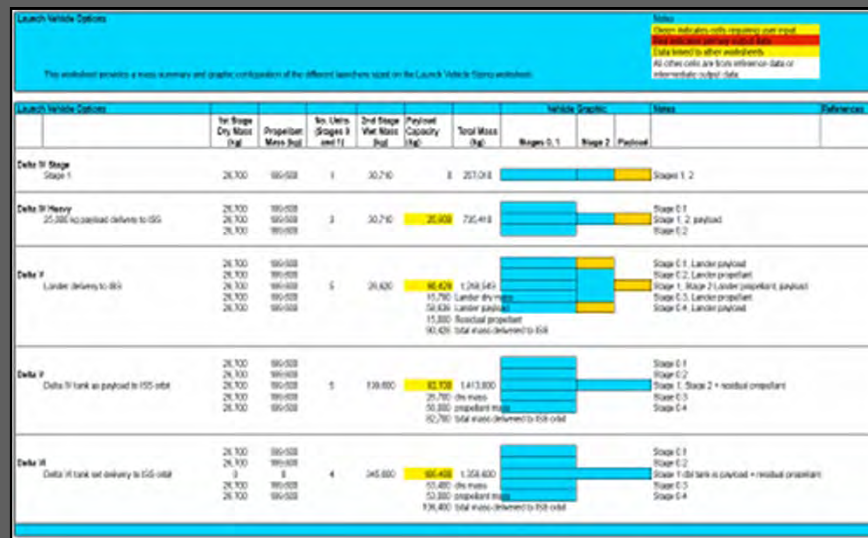
United States' Delta Launch Vehicles

Russia's Proton M Launch Vehicle

ESA's Ariane 5 Launch Vehicle

Delta IV Derived Launch Systems





All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

Delta IV Heavy

- Delta IV Heavy
  - 25,800 kg to LEO
- Stage 1
  - 26,700 kg dry mass
  - 199,600 kg propellant
- Stage 0 (2 boosters)
  - 26,700 kg dry mass each
  - 199,600 kg propellant each
- Stage 2 (upper stage)
  - 3,490 kg dry mass
  - 27,200 kg propellant
- Assumed Cost: $160 M

- Payloads limited to Delta IV and Ariane 5
  - All transfer habitat modules
  - Crew Excursion Vehicle
- Payloads acceptable Delta IV, Proton M, and Ariane 5
  - Transfer habitat attachments
  - Lander attachments
  - Propellant
  - Water
  - Consumable
  - Additional racks and crew consumables
  - Power systems
  - Depot systems

Delta V Tanker

- Delta V Tanker
  - 82,700 kg to LEO
- Stage 1
  - 26,700 kg dry mass
  - 199,600 kg propellant
- Stage 0 (4 boosters)
  - 26,700 kg dry mass each
  - 199,600 kg propellant each
- Stage 2
  - 26,700 kg dry mass
  - 199,600 kg propellant

- Assumed Cost: $300 M
  - Includes stages 0 – 2
- Payload
  - 26,700 kg Delta IV tank
  - 56,000 kg residual propellant in second stage
  - 82,700 kg total delivered mass

Delta V Double Tanker

- Delta V Tanker
  - 106,400 kg to LEO
- Stage 1 (double tank set)
  - 53,400 kg dry mass
  - 398,000 kg propellant
- Stage 0 (4 boosters)
  - 26,700 kg dry mass each
  - 199,600 kg propellant each

- Assumed Cost: $310 M
  - Includes stages 0 and custom designed stage 1
- Payload
  - 26,700 kg Delta IV tank
  - 53,000 kg residual propellant in second stage
  - 106,400 kg total delivered mass

Delta V Lander

- Delta V Lander
  - 90,400 kg to LEO
- Stage 1
  - 26,700 kg dry mass
  - 199,600 kg propellant
- Stage 0 (4 boosters)
  - 26,700 kg dry mass each
  - 199,600 kg propellant each
- Stage 2 (Lander)
  - 16,800 kg dry mass
  - 64,400 kg propellant

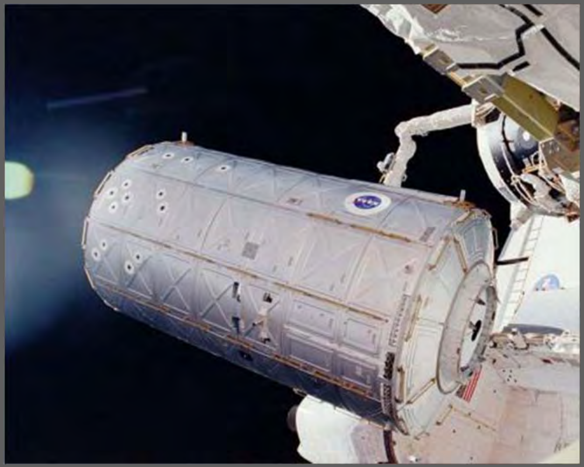
- Assumed Cost: $250 M
  - Includes stages 0 - 1
  - Stage 2 / Lander cost not included
- Payload
  - 16,800 kg Lander
  - 58,600 kg payload on Lander
  - 15,000 kg residual propellant in Lander
  - 90,400 kg total delivered mass

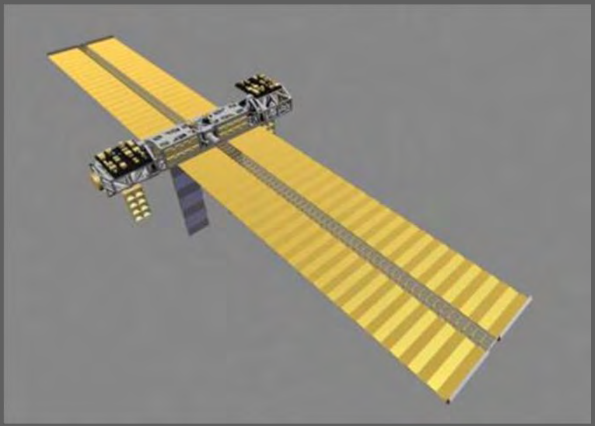
International Space Station Utilization

- The International Space Station has a 10 year mission beyond final assembly in 2010. After completion of this mission, in the 2020 time frame, it is proposed in this scenario to be used as a space port for the assembly of the Mars Ship.
- Possible Scenarios:
  - ISS becomes part of an International Consortium to facilitate commercial space development.
  - Primary support is provided through International Government development of Lunar and Mars missions.
  - Option: ISS is gradually moved to a lower inclination with each re-boost operation to facilitate more efficient payload delivery

ISS Design Compatibility

- The ISS and all existing space systems are used as the starting point for the Mars Ship design.
  - ISS Pressurized Modules
    - Existing launch vehicles are capable of launching ISS sized modules, so a modified space station module is used in the design
  - ISS hatch and docking systems
  - ISS internal racks
  - ISS robotic systems for assembly
  - ISS derived power and thermal systems



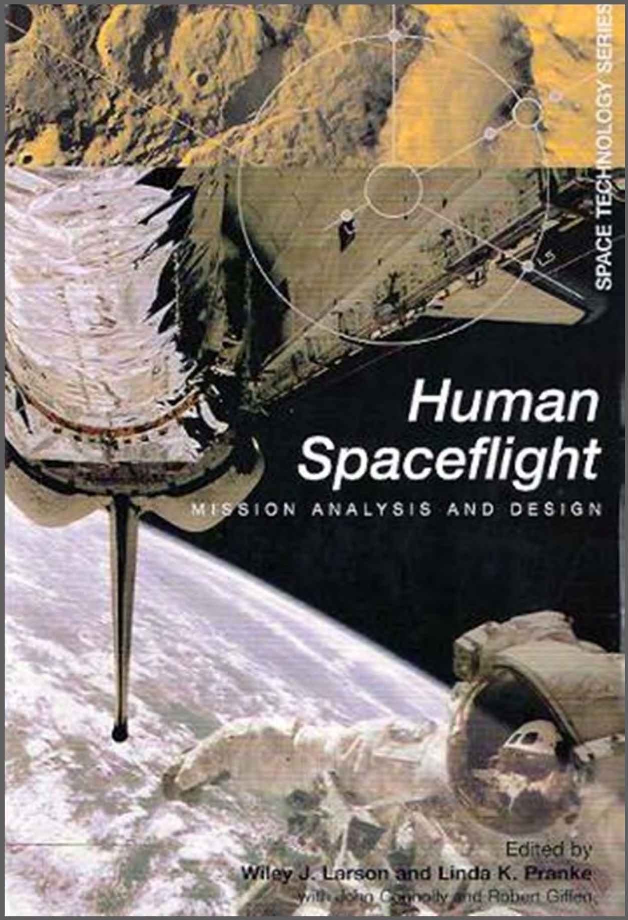


Mission Analysis and Design

MS-SPACE ARCHITECTURE
SICSA

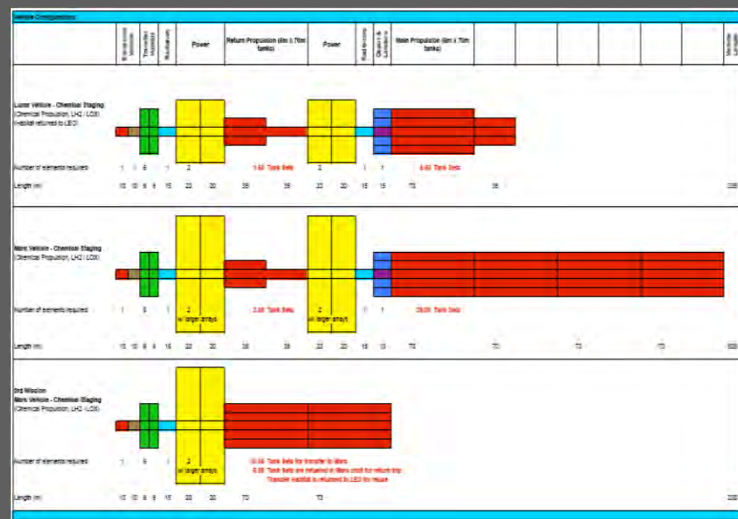
System Sizing

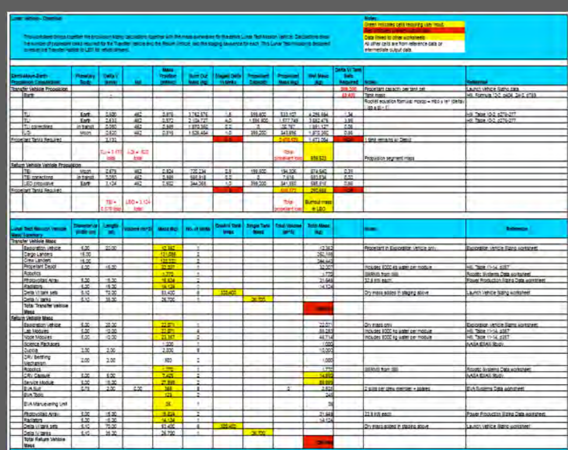
- All major systems were sized based on the formulas, historical data, and rules of thumb from the text, “Human Space Flight: Mission Analysis and Design,” editied by Larson and Pranke. Excel spreadsheets were developed and used for the sizing the following items:
  - Propellant calculations for each vehicle and each phase of the mission
  - Propellant tank sizing for each vehicle
  - Habitat mass and volume sizing for crew size and mission duration
  - Habitat systems sizing for volumetric layout
  - Historical data and “Rules of Thumb” on other items for approximate mass requirements and program plans

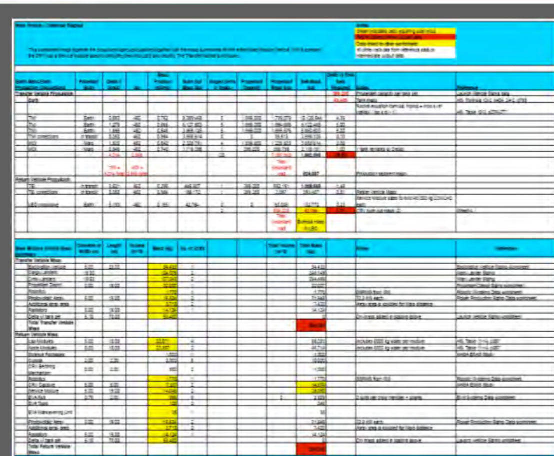


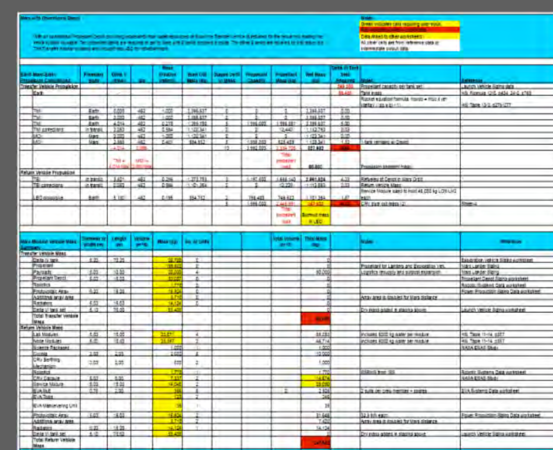
All calculations are based on the author’s interpretation of the formulas, data, and rules of thumb found in the text, “Human Spaceflight: Mission Analysis and Design” by Larson & Pranke. This presentation is for educational purposes only.

Lunar and Mars Vehicle Sizing









Lunar and Mars Vehicle Configuration

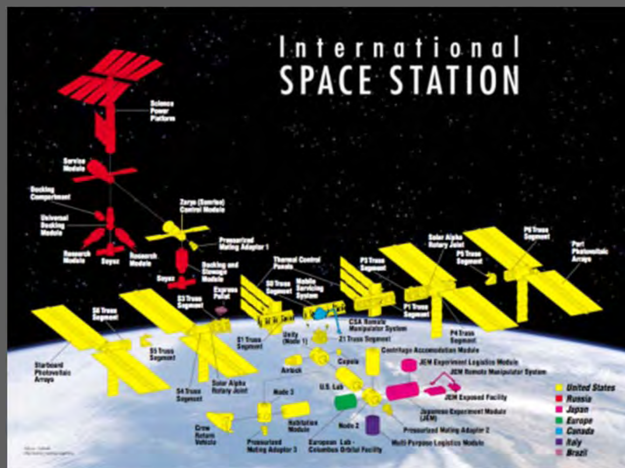
Mars Ship Configuration

1. 15 dbl tank stages for TMI + 5 dbl tank stages for MOI
2. 2 Crew Landers and 2 Cargo Landers attached to Propellant Depot
3. 2 Solar Power Units w/ twice the array area as the Lunar vehicle
4. 1 dbl tank and 2 single tank stages for TEI
5. 2 Solar Power Units with twice the array area as at earth orbit + 1 radiator unit
6. Transfer Habitat (6 modules)
7. 2-Crew Return Vehicles
8. 1-Crew Excursion Vehicle

Lunar Test Mission Configuration

1. 3 single & 4 dbl tank stages for TLI + 1 dbl tank stage for LOI
2. 2 Crew Landers and 2 Cargo Landers attached to Propellant Depot
3. 2 Solar Power Units
4. 1 dbl tank and 2 single tank stages for TEI
5. 2 Solar Power Units + 1 radiator unit
6. Transfer Habitat (6 modules)
7. 2-Crew Return Vehicles
8. 1-Exploration / Crew Transfer Vehicle

Vehicle Size Comparisons



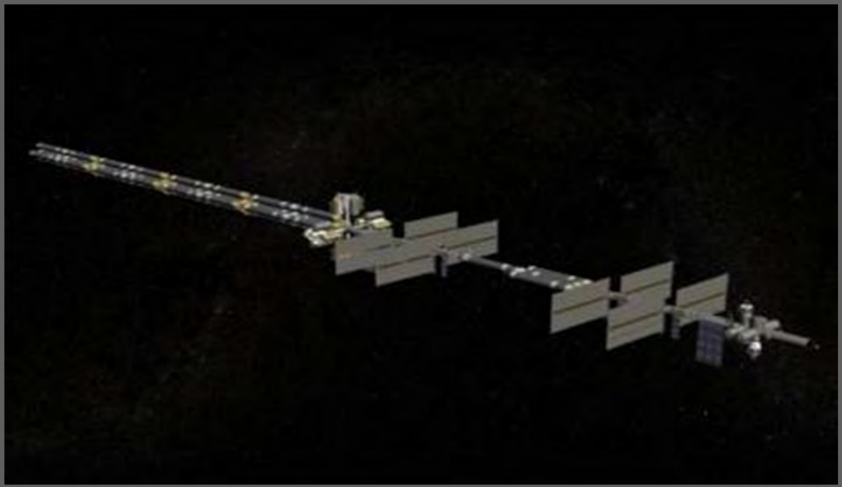
International Space Station

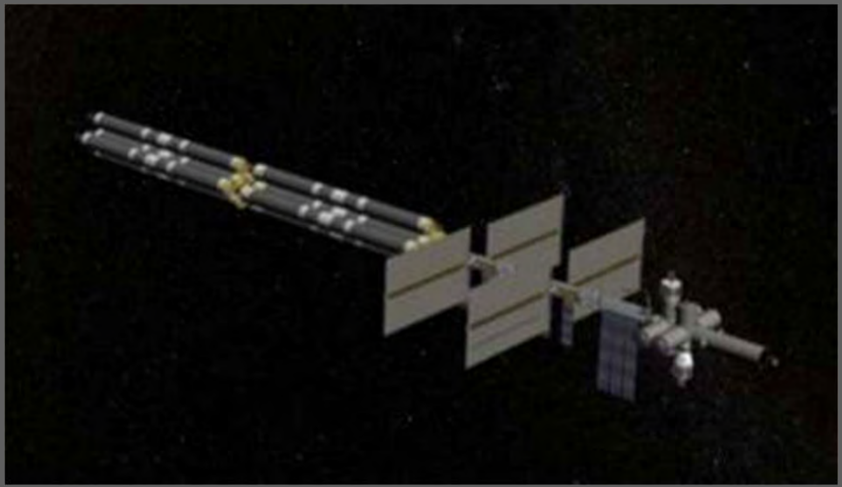
- Mass: 232,693 kg
- Length:58.2 m along truss
- Width: 44.5 m from Destiny to Zvezda
- Height:27.4 m
- Living volume: 424.75 m³
- Crew Size: 6

Lunar Test Vehicle

- Mass: 4,295,684 kg wet mass
  - 247,932 kg Transfer Habitat mass
- Length: 335 m
- Width: 76 m (span of solar arrays)
- Height: 39 m
- Living volume: 826 m³
- Crew Size: 8

Vehicle Size Comparisons





Mars Ship

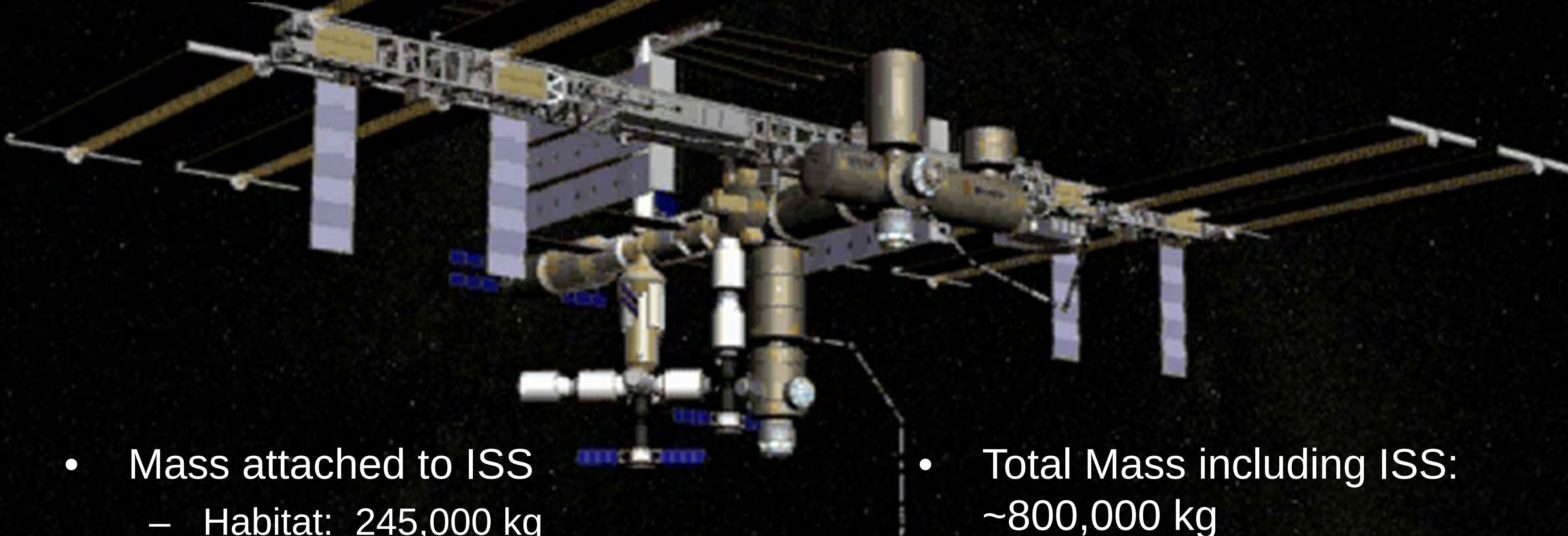
- Mass: 10,128,544 kg wet mass
  - 247,932 kg Transfer Habitat mass
- Length: 505 m
- Width: 76 m (span of solar arrays)
- Height: 39 m
- Living volume: 826 m^3
- Crew Size: 8

Mars Ship after 3rd Mission

- Mass: 3,396,637 kg wet mass
  - 247,932 kg Transfer Habitat mass
- Length: 230 m
- Width: 76 m (span of solar arrays)
- Height: 39 m
- Living volume: 826 m^3
- Crew Size: 8

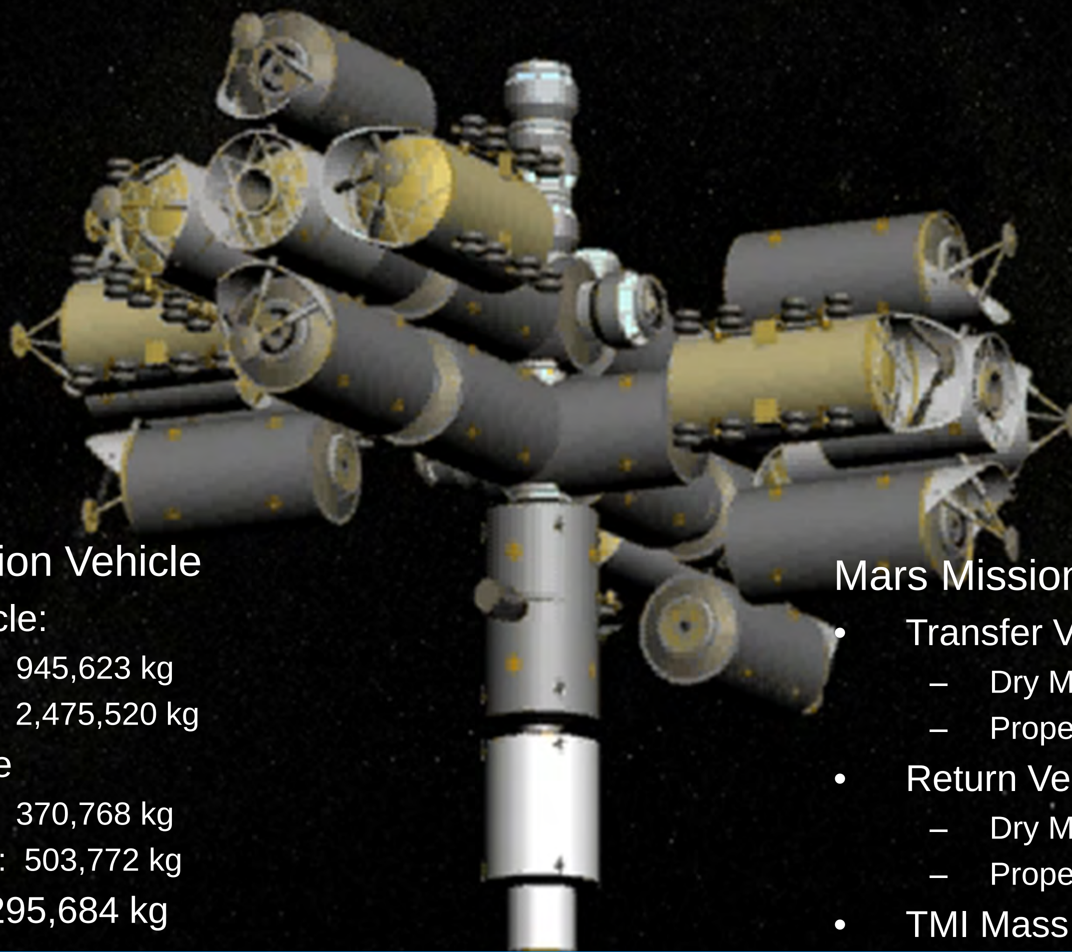
All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

Transfer Habitat and Lander Assembly Operations at ISS



- Mass attached to ISS
  - Habitat: 245,000 kg
  - 4 Landers: ~80,000 kg each
    - Includes 15,000 kg residual propellant in each Lander
  - Total: ~565,000 kg
- Total Mass including ISS: ~800,000 kg
  - Attached mass will be greater than total ISS mass
  - ISS re-boost will be by Exploration vehicle at lower end of Transfer Habitat

Tethered Assembly Concept



Lunar Test Mission Vehicle

- Transfer Vehicle:
  - Dry Mass: 945,623 kg
  - Propellant 2,475,520 kg
- Return Vehicle
  - Dry Mass: 370,768 kg
  - Propellant: 503,772 kg
- TLI Mass: 4,295,684 kg

Mars Mission Vehicle

- Transfer Vehicle:
  - Dry Mass: 1,692,037 kg
  - Propellant 7,397,550 kg
- Return Vehicle
  - Dry Mass: 354,732 kg
  - Propellant: 684,226 kg
- TMI Mass: 10,128,544 kg

Lunar and Mars Ship Staging

Trans-Mars Injection (TMI)

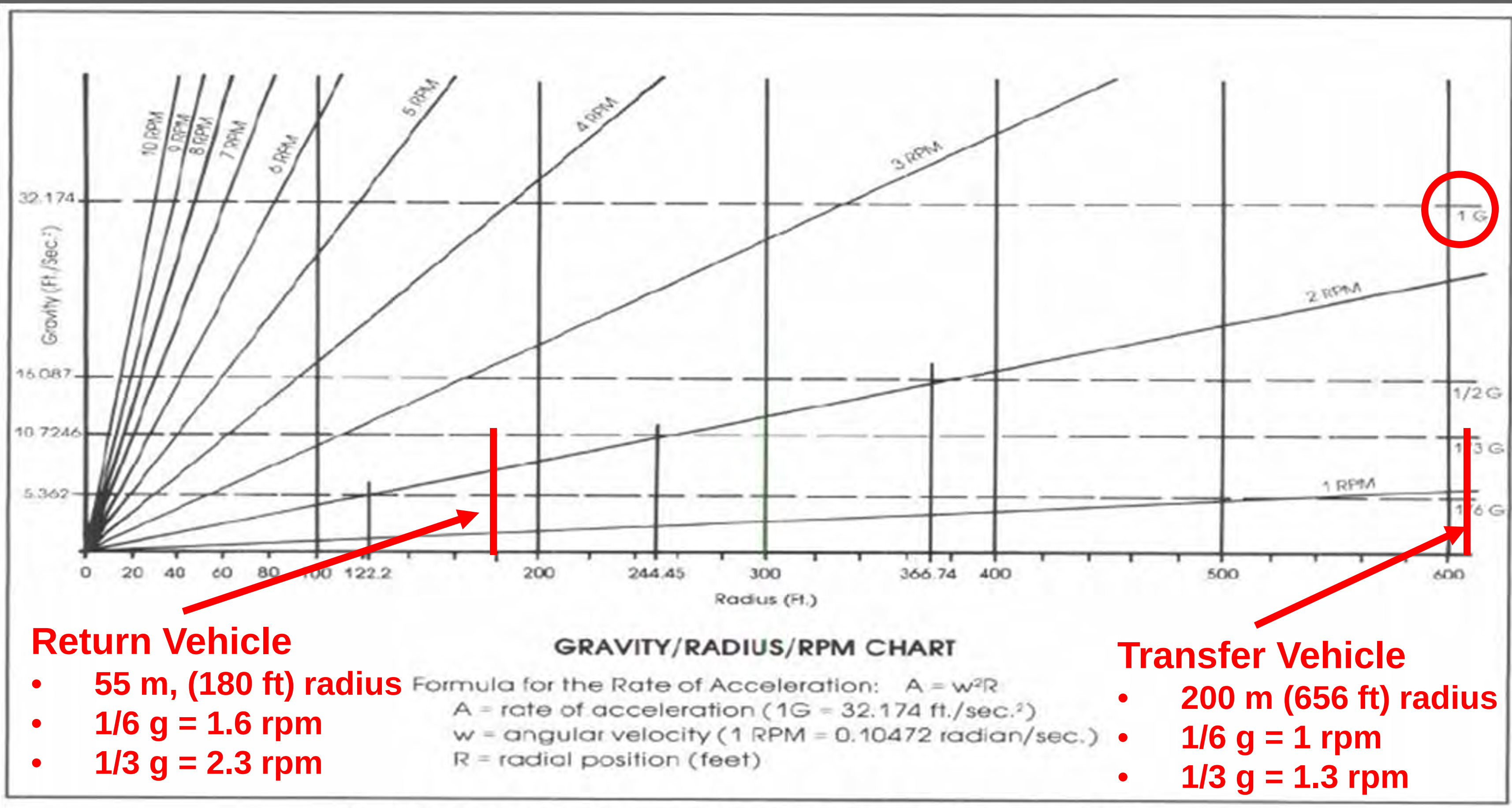
Lunar Test Mission Vehicle Staging

- TLI: 5.5 tanks
- LOI: 1 tank
- TEI: 0.5 tank
- LEO capture: 1 tank (The transfer habitat is brought into LEO orbit for refurbishment at the ISS)

Mars Mission Vehicle Staging

- TMI: 15 tanks
- MOI: 5 tanks
- TEI: 2 tanks
- LEO: 2 CRV vehicles deorbit (The transfer habitat cannot be saved until depot capability is in place in Mars orbit)

Variable Gravity Configuration



Return Vehicle

- **55 m, (180 ft) radius**
- **1/6 g = 1.6 rpm**
- **1/3 g = 2.3 rpm**

Transfer Vehicle

- **200 m (656 ft) radius**
- **1/6 g = 1 rpm**
- **1/3 g = 1.3 rpm**

Simulated Gravity Levels as a Function of Rotation Radii and Rates

Artificial Gravity Phase

Lunar Mission

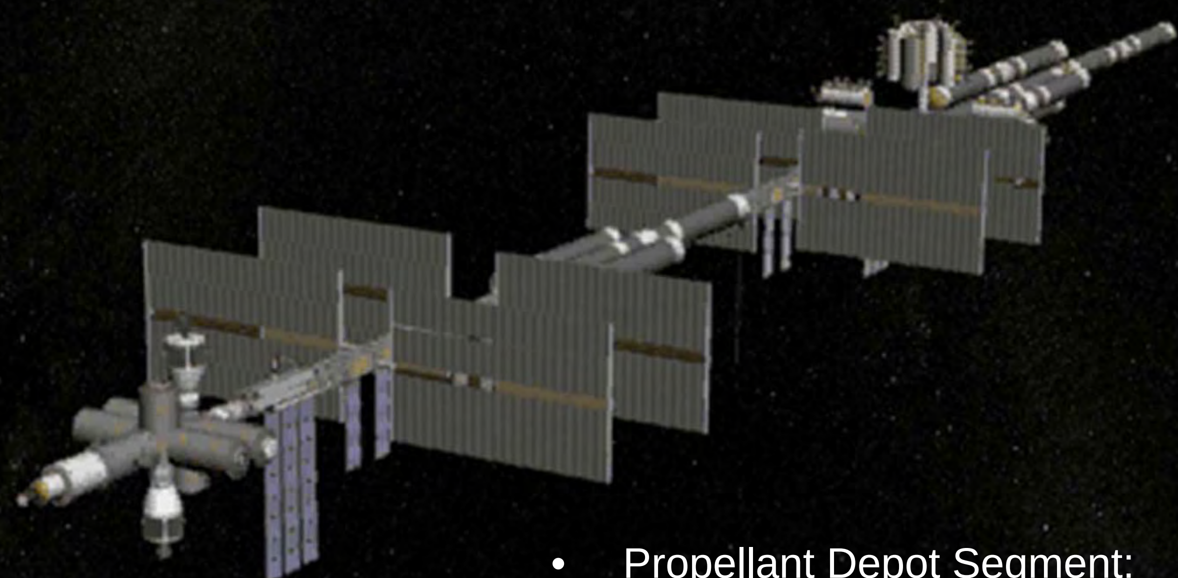
- Transfer Vehicle:
  - 1/6 g = 1 rpm
- Return Vehicle
  - 2 rpm = 1/4 g

Mars Mission

- Transfer Vehicle:
  - 1/3 g = 1.3 rpm
  - Animation is at 1.5 rpm
- Return Vehicle
  - 2 rpm = 1/4 g

All calculations are based on the authors interpretation of the formulas, data, and rules of thumb found in the text, “Human Spaceflight: Mission Analysis and Design” by Larson & Pranke. This presentation is for educational purposes only.

Lunar and Mars Orbit Operations



- Habitat Segment:
  - Dry Mass: 370,768 kg
  - Propellant: 503,772 kg
  - 2 Crew Landers: 254,485 kg
  - Total: 1,129,015 kg
- Propellant Depot Segment:
  - Propellant Depot: ~135,000 kg
  - Residual Propellant: ~
  - 2 Cargo Landers: 248,149 kg
  - Total: ~383,000 kg

MS-SPACE ARCHITECTURE SICSA

Reusable Lunar and Mars Lander Sizing

Surface Payloads Mass Summary

This worksheet is used to calculate the total landed payload mass. Add and modify as needed. Cells are linked to the Lander Sizing worksheets.

Notes
Green indicates cells requiring user input.
Red indicates primary output data
Data linked to other worksheets
All other cells are from reference data or intermediate output data.

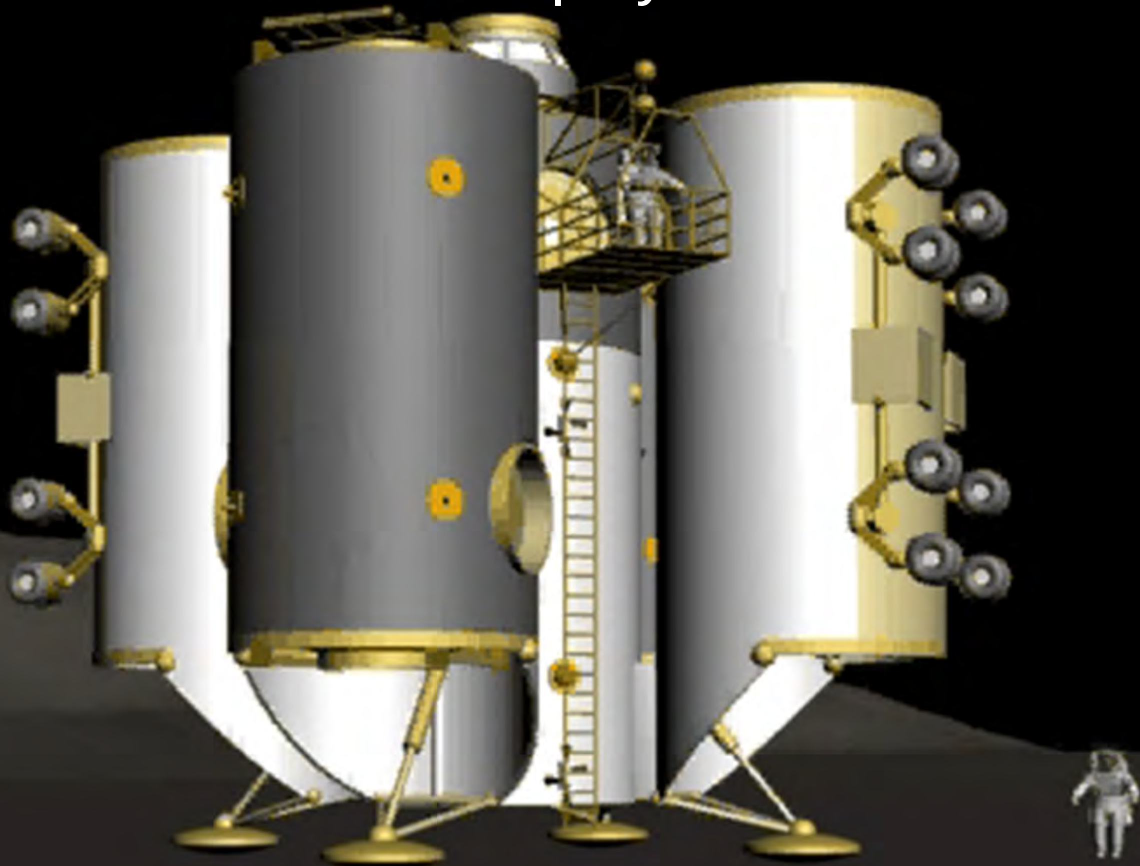
	Diameter or Width (m)	Length (m)	Volume (m^3)	Mass (kg)	No. of Units	Total Volume (m^3)	Total Mass (kg)	Notes	Reference
Surface Habitat Modules									
Lab Modules	5.00	10.00		22,685	4		90,739	Includes 8000 kg water per module	HS, Table 11-14, p357
Node Modules	5.00	10.00		23,960	2		47,920	Includes 8000 kg water per module	HS, Table 11-14, p357
Surface Equipment									
Science Packages				1,000	1		1,000	Can be broken up into smaller payloads.	NASA ESAS Study
ISRU Packages				500	1		500	Can be broken up into smaller payloads.	NASA ESAS Study
Electrolysis Units				1,632	4		6,528	Utilizes lander propellant tanks, and produces 25,000 kg propellant per year, each.	Based on NASA / Boeing Study (5% scale per lander)
Surface Mobility Systems									
Pressurized Rover	5.00	10.00		18,000	1		18,000	Includes 8000 kg of water	NASA ESAS Study
Unpressurized Rover/Trailers	5.00	10.00		1,090	2		2,180		
UPR Attachements				500	4		2,000	Backhoe, Blade, Scoop, Core Drill	
EVA Suit	0.75	2.00	3.00	366	8	24	2,928	2 suits per crew member + spares	NASA ESAS Study
EVA Tools				123	2		246		
Surface Power									
Mars Nuclear Power Unit or Lunar Photovoltaic Array	5.00	5.00		10,000	2		20,000	25 kW each. Solar and Nuclear systems have similar total mass.	NASA ESAS Study
Power Management and Data equip				2,370	1		2,370	Includes 2.5 km power cables	NASA ESAS Study
Total Payload Mass to Surface							194,411		

All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

Reusable Lunar and Mars Lander Sizing Summary

- Lunar Crew Landers 1 & 3
  - Lander dry mass: 20,840 kg
  - Propellant: 60,000 kg
    - Descent: 47,000 kg
    - Ascent: 13,000 kg
  - Payload: 41,046 kg
  - Total Wet Mass: ~122,000 kg
- Lunar Cargo Landers 2 & 4
  - Lander dry mass: 14,840 kg
  - Propellant: 60,000 kg
    - Descent: 47,000 kg
    - Ascent: 13,000 kg
  - Payload: 56,159 kg
  - Total Wet Mass: ~131,000 kg
- Mars Crew Landers 1 & 3
  - Lander dry mass: 22,790 kg
  - Propellant: 64,000 kg
    - Descent: 22,000 kg
    - Ascent: 42,000 kg
  - Payload: 41,046 kg
  - Total Wet Mass: ~128,000 kg
- Mars Cargo Landers 2 & 4
  - Lander dry mass: 16,790 kg
  - Propellant: 52,000 kg
    - Descent: 22,000 kg
    - Ascent: 30,000 kg
  - Payload: 58,638 kg
  - Total Wet Mass: ~128,000 kg

Lander 1 Deployment



Primary Payloads

- Mission Operations Module
- EVA / Airlock Node
- Un-pressurized Rover

Lander 2 Deployment

Primary Payloads:

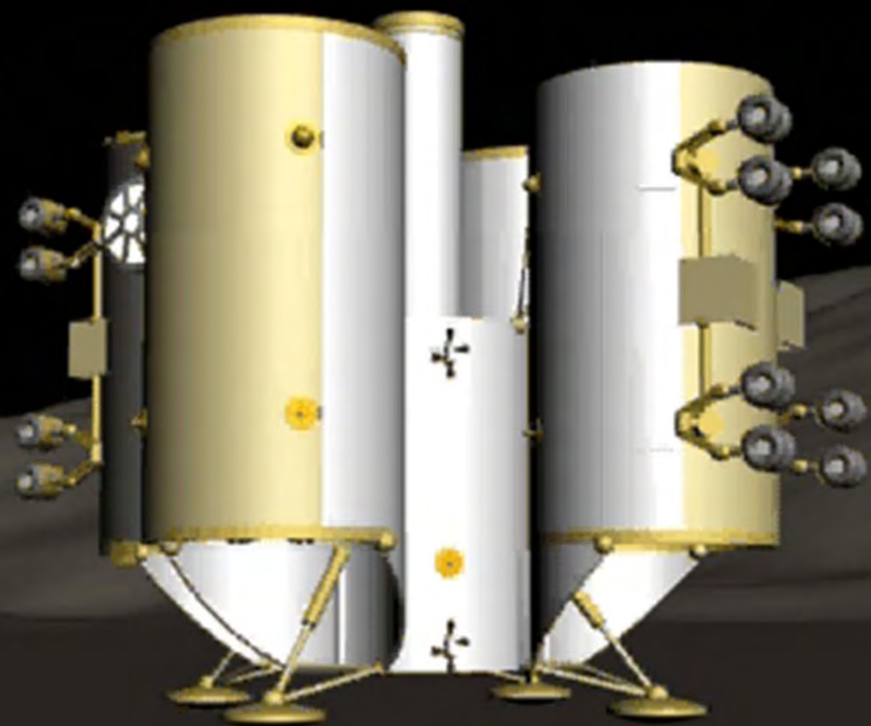
- Greenhouse Module
- Galley / Airlock Node
- Surface Equipment

Lander 3 Deployment

Primary Payloads:

- Materials Science Module
- Life Science Module
- Un-pressurized Rovers

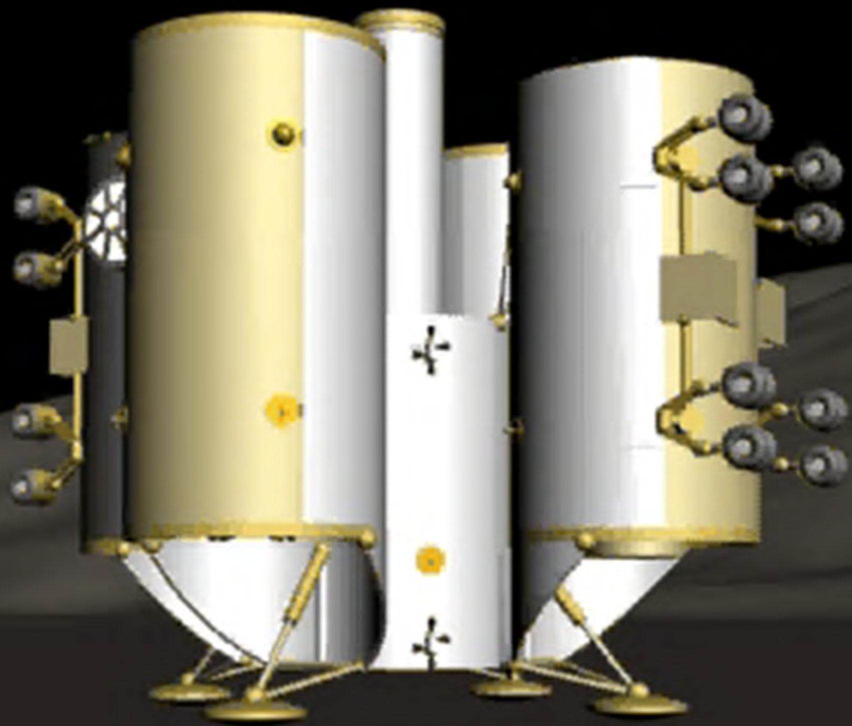
Lander 4 – Lunar Power System



Primary Payloads:

- Pressurized Rover
- Solar Power Module
- Surface Equipment

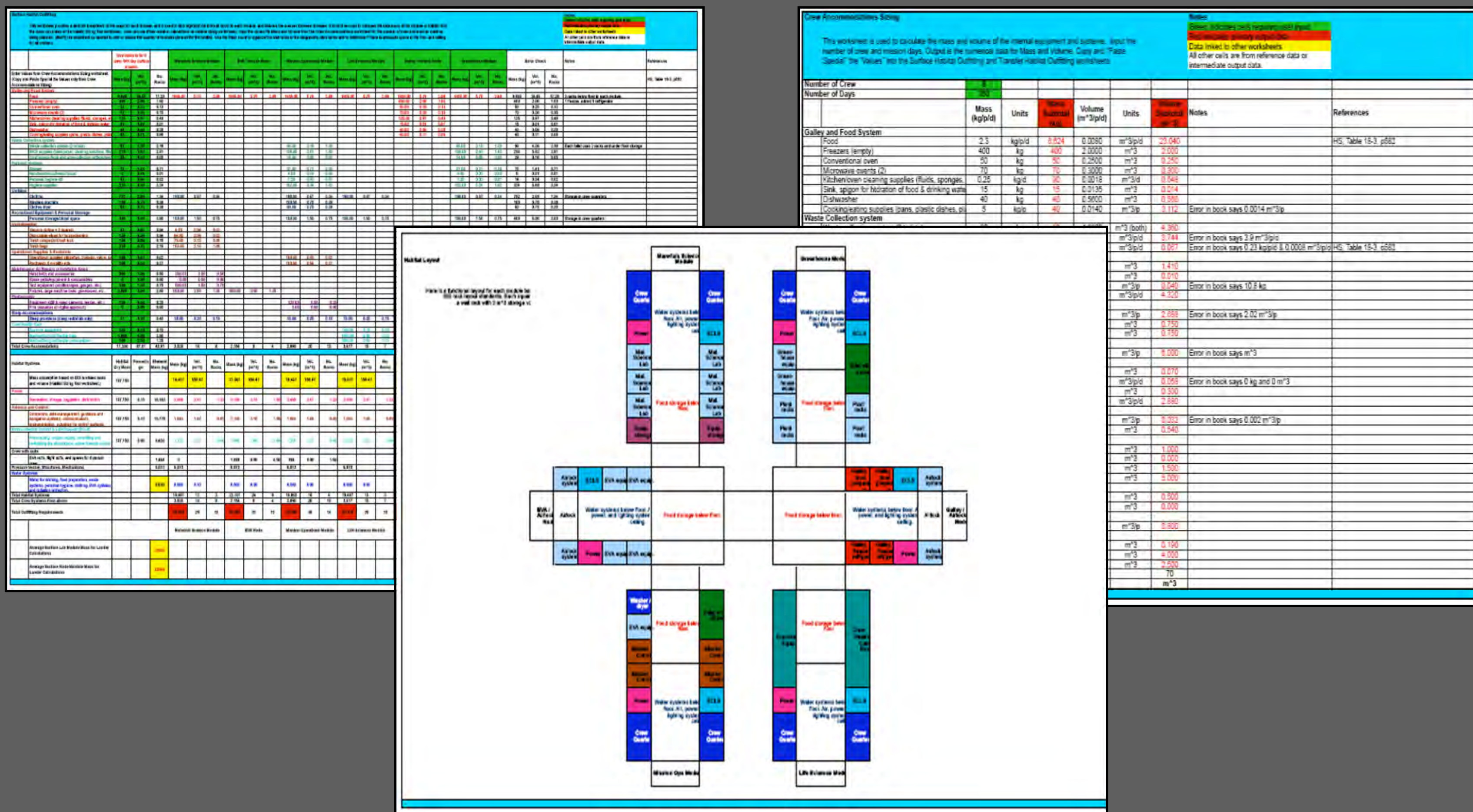
Lander 4 – Mars Power System



Primary Payloads:

- Pressurized Rover
- Nuclear Power Module
- Surface Equipment

Transfer and Surface Habitat Sizing



All calculations are based on the author’s interpretation of the formulas, data, and rules of thumb found in the text, “Human Spaceflight: Mission Analysis and Design” by Larson & Pranke. This presentation is for educational purposes only.

Lunar and Mars Outpost Assembly

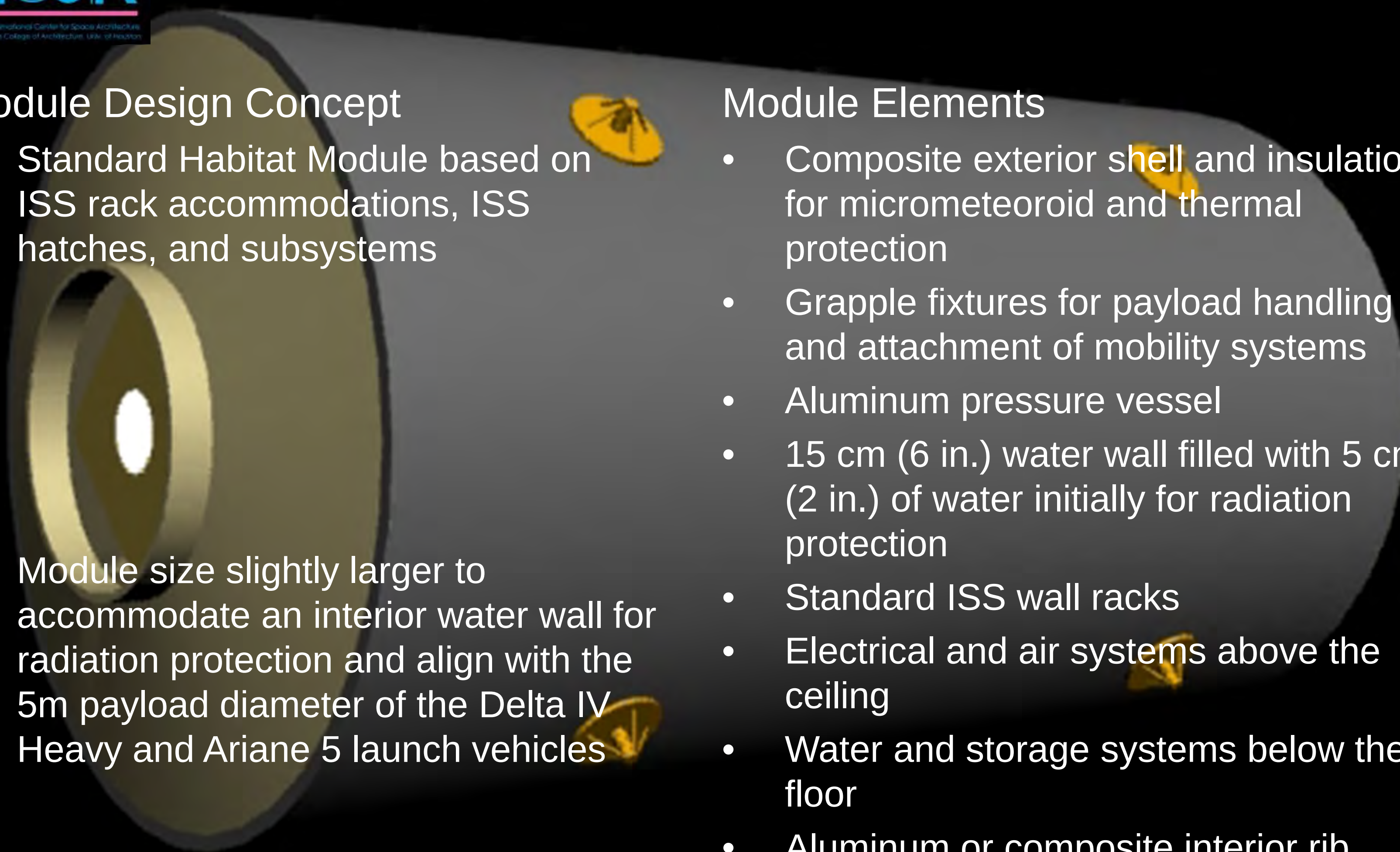
Surface Habitat:

- 6 pressurized modules
- Mass: 138,000 kg
- Volume: 825 m^3 (excluding water wall)
- Volume per person: 103 m^3
- Power: 56 kW
- Consumables: 21,500 kg
- Water: 48,000 kg (recycled)

Outpost Primary Payloads:

- 2 Un-pressurized Rovers
- 1 Pressurized Rover
- 56 kW Power Module
  - Solar at Moon
  - Nuclear at Mars
- 6 Habitat Modules
  - Mission Ops Module
  - Life Science Module
  - EVA / Airlock Node
  - Galley / Airlock Node
  - Materials Science Module
  - Greenhouse Module

Module Assembly Details



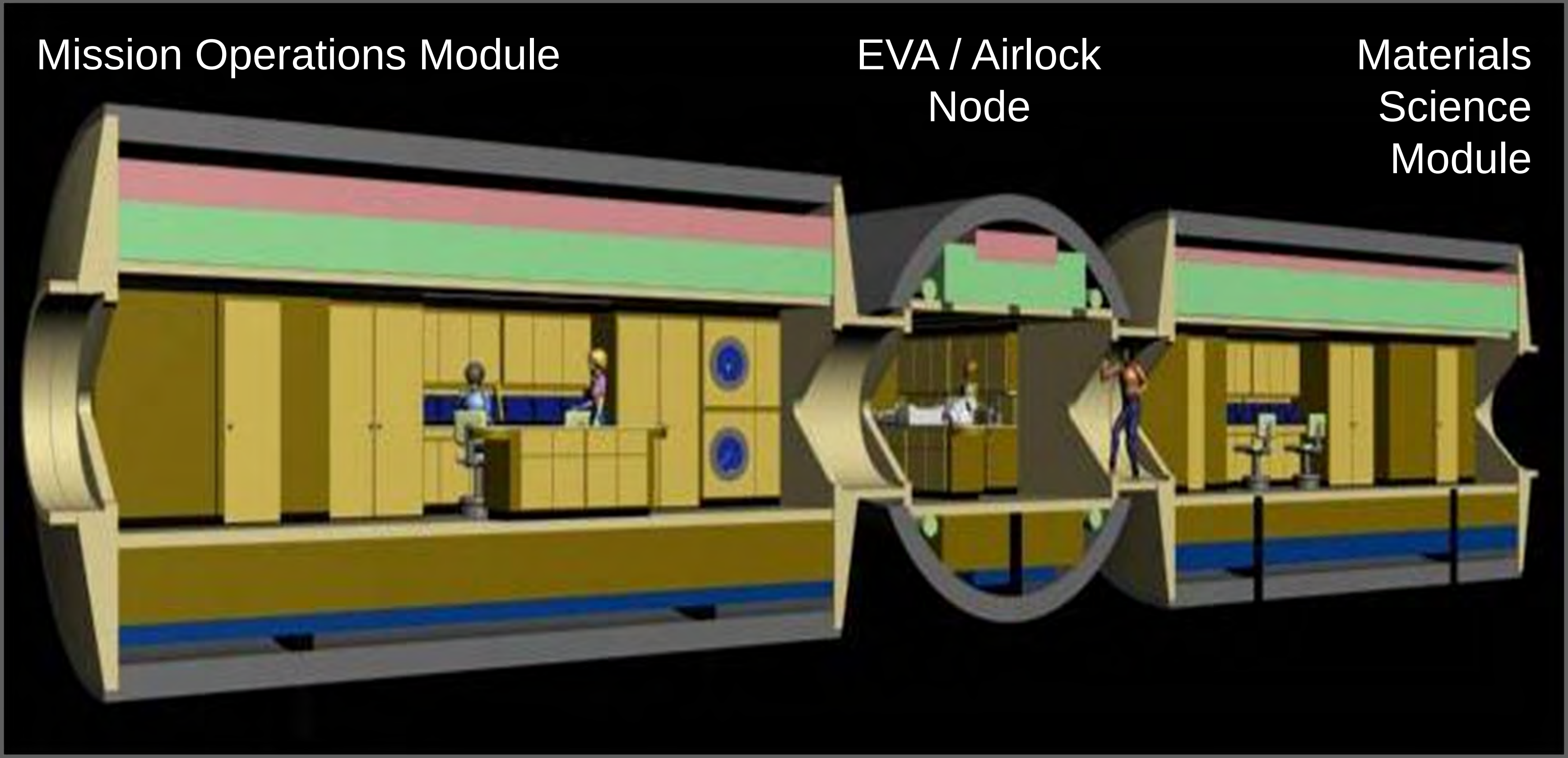
Module Design Concept

- Standard Habitat Module based on ISS rack accommodations, ISS hatches, and subsystems
- Module size slightly larger to accommodate an interior water wall for radiation protection and align with the 5m payload diameter of the Delta IV Heavy and Ariane 5 launch vehicles

Module Elements

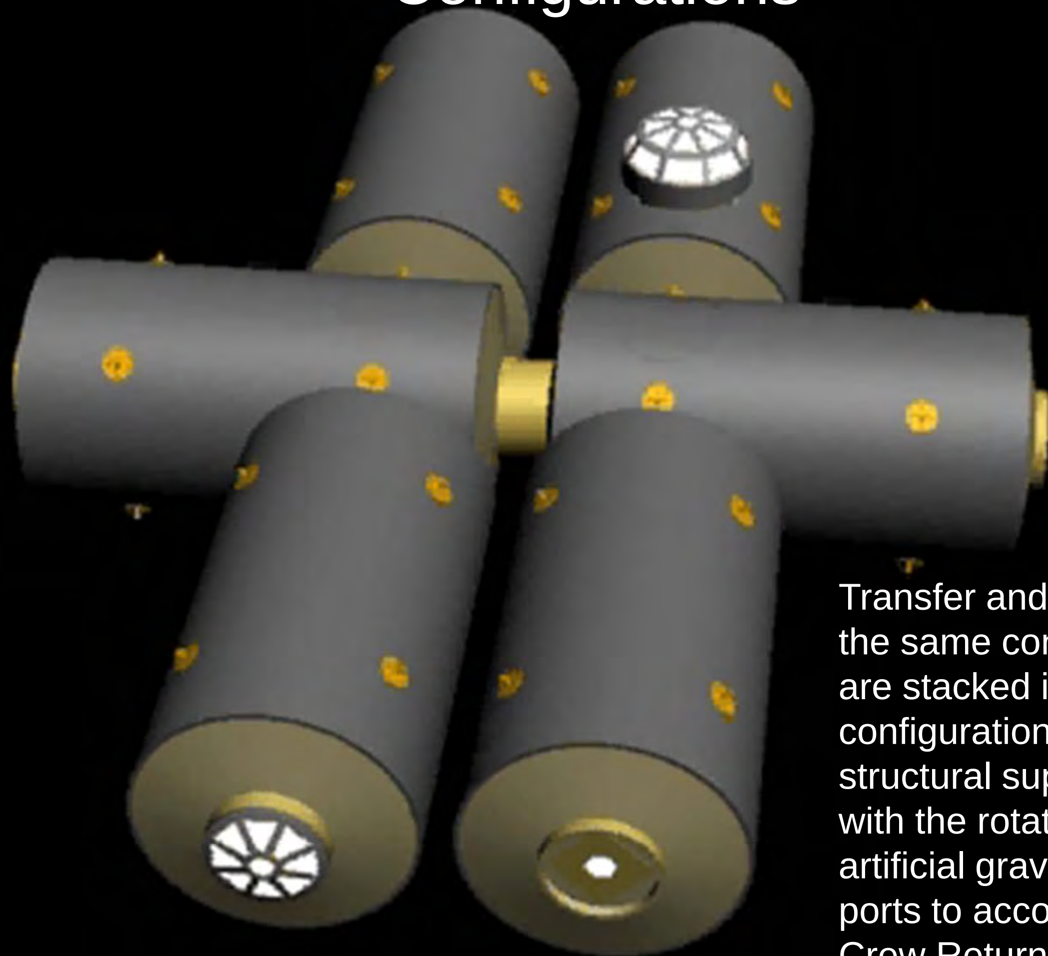
- Composite exterior shell and insulation for micrometeoroid and thermal protection
- Grapple fixtures for payload handling and attachment of mobility systems
- Aluminum pressure vessel
- 15 cm (6 in.) water wall filled with 5 cm (2 in.) of water initially for radiation protection
- Standard ISS wall racks
- Electrical and air systems above the ceiling
- Water and storage systems below the floor
- Aluminum or composite interior rib structure

Cross-Section of Habitat



Habitat Tour

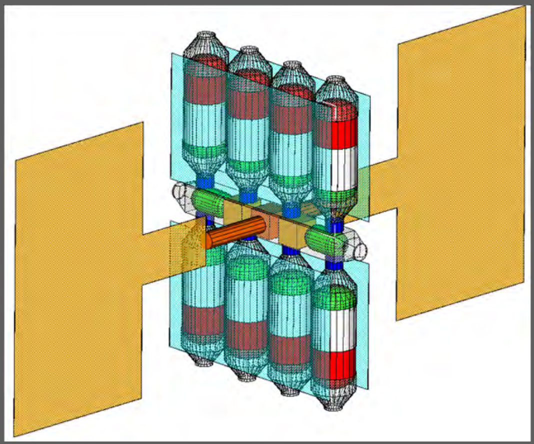
Transfer and Surface Habitat Configurations

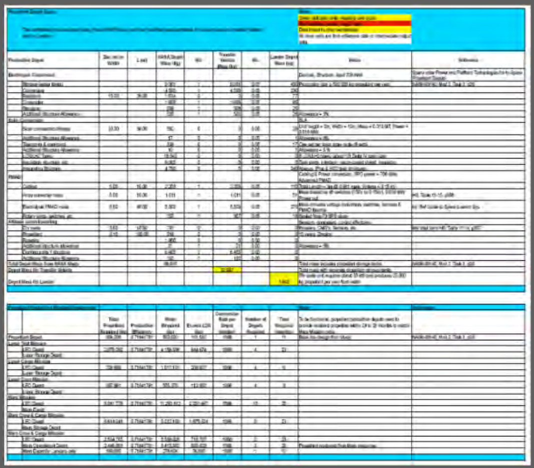


Transfer and Surface Habitats are in the same configuration except they are stacked in space transfer vehicle configuration to provide better structural support, better alignment with the rotation of the habitat for artificial gravity, and more docking ports to accommodate 4 Landers, 2 Crew Return Vehicles, and an Excursion Vehicle

Propellant Depot Sizing for Recurring Mars Missions

- Propellant Production Depot
  - Production: 500,000 kg per year
  - Propellant required: 2,500,000 kg
  - 3 Depots required, producing propellant from water over a 2 year period
    - 3,000,000 kg production capacity
    - 2,500,000 kg for return vehicle
    - 500,000 kg remaining for Landers and Exploration Vehicle
  - Option: 1 Depot sized up slightly could support missions on a 4 year cycle





Crew Excursion Vehicle Sizing

- Excursion Vehicle
  - Designed for 2 crew members to explore Phobos and Deimos in 2 week excursions from the Mars Ship in a 500 km orbit around Mars
  - Includes 2 pressurized maneuvering units for surface exploration
  - Dry Mass: 22,071 kg
  - Wet Mass: 34,433 kg

Exploration Vehicle Sizing

This worksheet is used to calculate the total gross (wet) mass of the Exploration Vehicle, and to calculate propellant requirements including propellant tank sizes. Payload data is input automatically using a standard habitat module from the Habitat Sizing Tool. The Mars Mission is sized for exploration of Phobos and Deimos. The Lunar Mission is assumed to go to an asteroid.

Notes
- Green indicates cells requiring user input.
- Red indicates primary output data.
- Data linked to other worksheets
- All other cells are from reference data or intermediate output data.

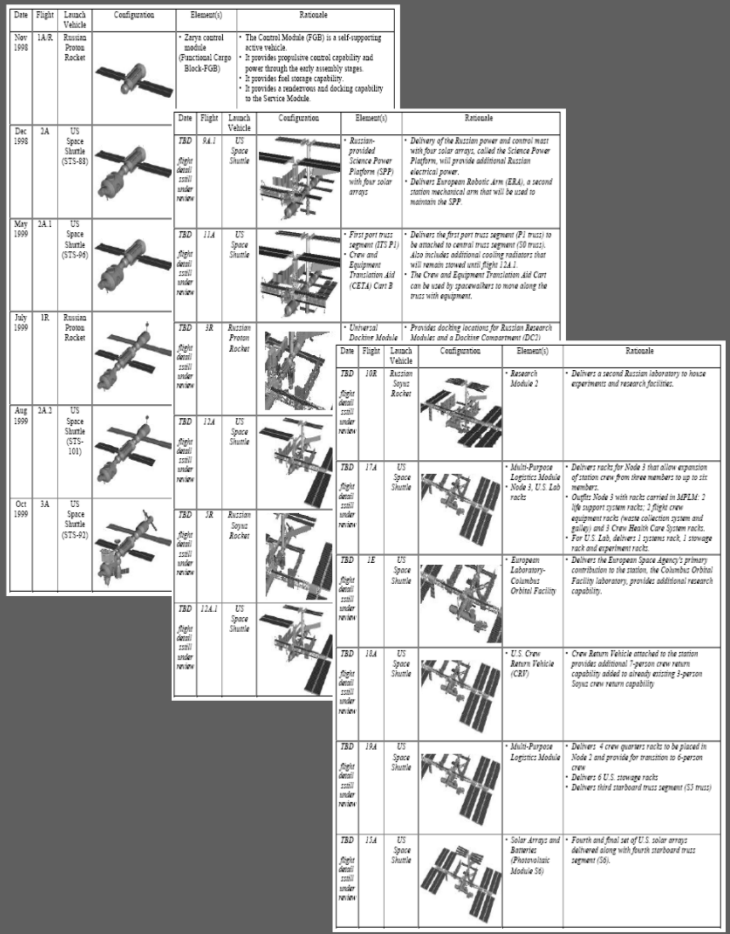
Reusable Cargo Lander	Planetary Body	Delta V (km/s)	Isp	Mass Fraction (mf/mo)	Dry Mass (kg)	Propellant Mass (kg)	Wet Mass (kg)	Notes	Reference
Mars orbit to Deimos Transfer Orbit	Mars	0.200	390	0.938	32,677	1,755	34,433		
Deimos Transfer Orbit to Deimos Surface	Mars	0.700	390	0.800	27,209	5,468	32,677		
Deimos Transfer Orblet to Phobos Transfer Orbit	Mars	0.300	390	0.909	25,155	2,054	27,209		
Phobos Transfer Orbit to Phobos Surface	Mars	0.500	390	0.853	22,071	3,084	25,155		
						12,362	22,071	Exploration vehicle module mass assumed to be equivalent to one lab module	

Lander Tank Sizes	Data	Units	Notes	
Propellant	12,362	kg	Maximum lander propellant load is input here automatically to size standard tanks for all four landers	Use "Tank Sizing Tool" for verification and more detailed information.
LOX	10297.3524	kg		
Outside diameter	5	m		
Inside diameter	4.9	m		
Length of LOX tank	[illegible]	m	Length includes half spherical end domes and wall thickness	
LH2	2064.41519	kg		
Outside diameter	5.00	m		
Inside diameter	4.9	m		
Length of LH2 tank	[illegible]	m	Length includes half spherical end domes and wall thickness	
Length of LOX & LH2 tank in a stacked configuration	[illegible]	m	Length includes half spherical end domes and wall thickness	

Program Planning

ISS Assembly

- The space station will be assembled in about 45 flights over 15 years and then operated for an additional 10 years.
  - 28 US Assembly Flights
  - 7 US Utilization Flights
  - 10 Russian Flights

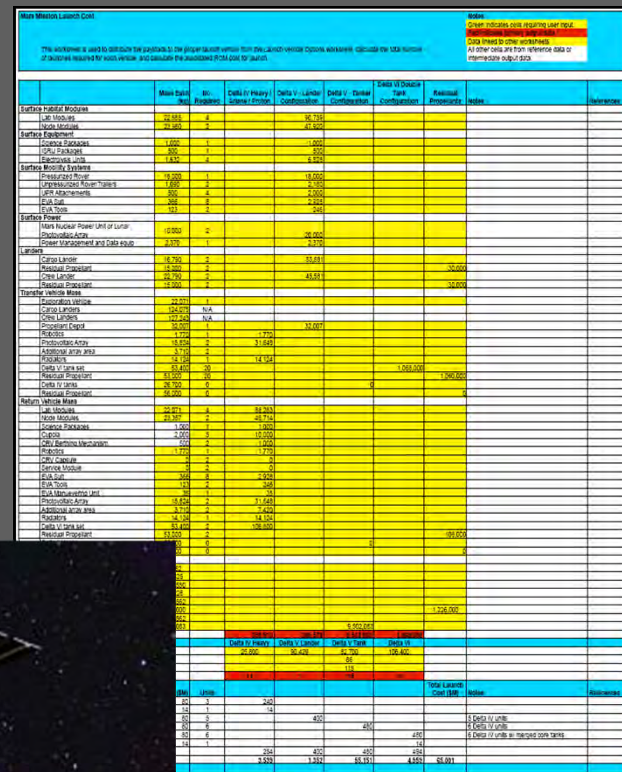


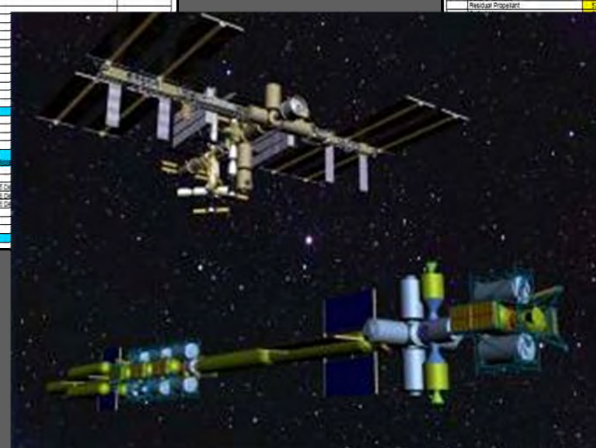
Date	Flight	Launch Vehicle	Configuration	Element(s)	Rationale
Nov 1998	1A/R	Russian Proton Rocket		• Zarya control module (Functional Cargo Block-FGB)	• The Control Module (FGB) is a self-supporting active vehicle. • It provides propulsive control capability and power through the early assembly stages. • It provides fuel storage capability. • It provides a rendezvous and docking capability to the Service Module.
Dec 1998	2A	US Space Shuttle (STS-88)			
May 1999	2A.1	US Space Shuttle (STS-96)			
July 1999	1R	Russian Proton Rocket			
Aug 1999	2A.2	US Space Shuttle (STS-101)			
Oct 1999	3A	US Space Shuttle (STS-92)			

Date	Flight	Launch Vehicle	Configuration	Element(s)	Rationale
TBD flight detail sstill under review	9A.1	US Space Shuttle		• Russian-provided Science Power Platform (SPP) with four solar arrays	• Delivery of the Russian power and control mast with four solar arrays, called the Science Power Platform, will provide additional Russian electrical power. • Delivers European Robotic Arm (ERA), a second station mechanical arm that will be used to maintain the SPP.
TBD flight detail sstill under review	11A	US Space Shuttle		• First port truss segment (ITS P1) • Crew and Equipment Translation Aid (CETA) Cart B	• Delivers the first port truss segment (P1 truss) to be attached to central truss segment (S0 truss). Also includes additional cooling radiators that will remain stowed until flight 12A.1. • The Crew and Equipment Translation Aid Cart can be used by spacewalkers to move along the truss with equipment.
TBD flight detail sstill under review	3R	Russian Proton Rocket		• Universal Docking Module	• Provides docking locations for Russian Research Modules and a Docking Compartment (DC2)
TBD flight detail sstill under review	12A	US Space Shuttle			
TBD flight detail sstill under review	5R	Russian Soyuz Rocket			
TBD flight detail sstill under review	12A.1	US Space Shuttle			

Date	Flight	Launch Vehicle	Configuration	Element(s)	Rationale
TBD flight detail sstill under review	10R	Russian Soyuz Rocket		• Research Module 2	• Delivers a second Russian laboratory to house experiments and research facilities.
TBD flight detail sstill under review	17A	US Space Shuttle		• Multi-Purpose Logistics Module • Node 3, U.S. Lab racks	• Delivers racks for Node 3 that allow expansion of station crew from three members to up to six members. • Outfits Node 3 with racks carried in MPLM: 2 life support system racks; 2 flight crew equipment racks (waste collection system and galley) and 3 Crew Health Care System racks. • For U.S. Lab, delivers 1 systems rack, 1 stowage rack and experiment racks.
TBD flight detail sstill under review	1E	US Space Shuttle		• European Laboratory-Columbus Orbital Facility	• Delivers the European Space Agency's primary contribution to the station, the Columbus Orbital Facility laboratory, provides additional research capability.
TBD flight detail sstill under review	18A	US Space Shuttle		• U.S. Crew Return Vehicle (CRV)	• Crew Return Vehicle attached to the station provides additional 7-person crew return capability added to already existing 3-person Soyuz crew return capability
TBD flight detail sstill under review	19A	US Space Shuttle		• Multi-Purpose Logistics Module	• Delivers 4 crew quarters racks to be placed in Node 2 and provide for transition to 6-person crew • Delivers 6 U.S. stowage racks • Delivers third starboard truss segment (S5 truss)
TBD flight detail sstill under review	15A	US Space Shuttle		• Solar Arrays and Batteries (Photovoltaic Module S6)	• Fourth and final set of U.S. solar arrays delivered along with fourth starboard truss segment (S6).

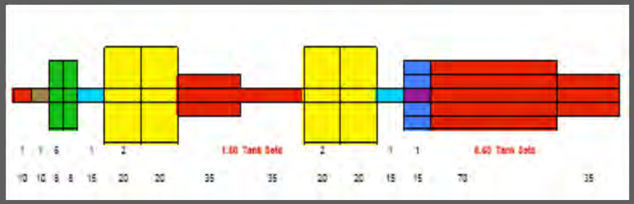
Lunar and Mars Vehicle Assembly Launches



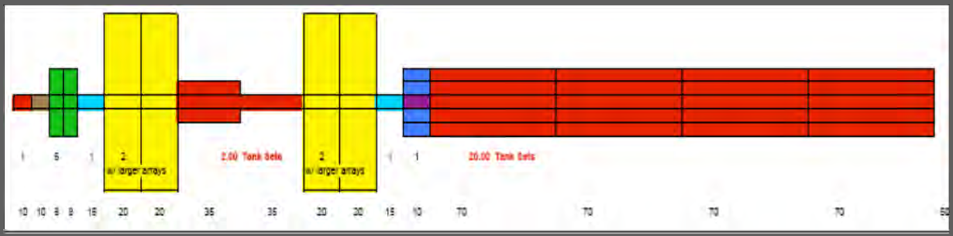


Lunar and Mars Ship Assembly Launch Summary

- The Lunar Test Mission requires about 52 launches over 8 years (6-7 launches per year)
  - 12 payload delivery flights from a Delta IV Heavy, Proton M, or Ariane 5
  - 4 Delta V Lander flights
  - 5 Delta V double tanker flights
  - 30 Delta V Tanker flights for propellant delivery, or about twice this many flights from current heavy lift vehicles
- The Mars Mission requires about 142 launches over 13 years (11 launches per year)
  - 10 payload delivery flights from a Delta IV Heavy, Proton M, or Ariane 5
  - 4 Delta V Lander flights
  - 115 Delta V Tanker flights for water deliver, or 86 flights for propellant deliver, or twice this many flights from current heavy lift vehicles



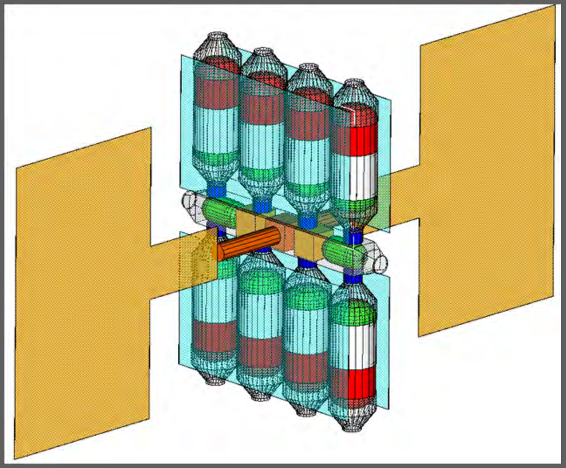
Lunar Test Mission Vehicle



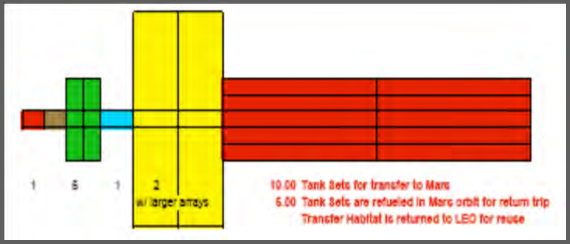
Mars Mission Vehicle

Recurring Mars Missions

- After the 3rd mission to Mars, a propellant production capability is put in place for the reusable Landers and reusable transfer vehicle.
- Recurring missions would require 44 launches over 4 years (11 flights per year)
  - 1 payload delivery flight from a Delta IV Heavy, Proton M, or Ariane 5
  - 0 Delta V Lander flights
  - 10 Delta V double tanker flights
  - 33 Delta V Tanker flights for water deliver, or 24 flights for propellant deliver, or twice this many flights from current heavy lift vehicles

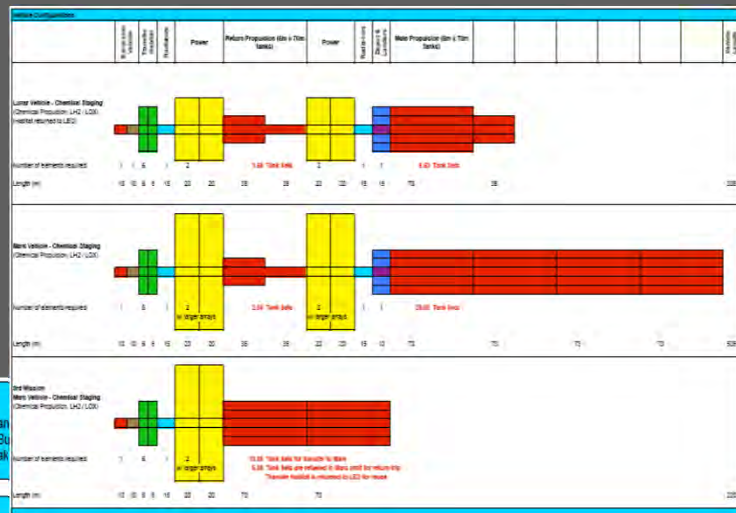


Propellant Production Depot



Recurring Mars Mission Vehicles

Lunar and Mars Program Cost & Schedule



Program Plans

This worksheet is used to plan out an overall program by year to calculate both total program an
Development cost are built up to $2B per year to match ISS development cost. This Program Bu
cost of about $121 B. Because the program is spread out over 25 years, the per year cost peak

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Program Development													
Mission concept developmen	1	1											
Phase A design		10	10	10	10								
Phase B design				100	100	200	200	100	100				
Phase C build						1,000	2,000	2,000	2,000	2,000	2,000	2,000	1,000
Nuclear power development and test				10	100	500	500	500	500	500	500	500	500
Lunar Test Mission													
Transfer habitat assembly at ISS												500	
Lander assembly													500
Launch and assemble propulsion elements								2,000	2,000	2,000	2,000	2,000	2,000
Final assembly and checkout													
Transfer to Lunar orbit													
Lunar surface exploration, 2025													
Return to Earth orbit													
Lunar Program Cost													
Mars Mission 1													
Refurbish transfer habitat for Mars mission													
Phase C build													1,000
Launch and assemble propulsion elements										1,000	1,000	1,000	1,000
Attach transfer habitat to ISS and refurbish													
Assembly landers													
Final assembly and checkout													
Transfer to Mars orbit													
Mars surface exploration, 2032													
Return to Earth orbit													
Mars Program Cost													
Cost per Year	1	11	10	120	210	1,700	2,700	4,600	4,600	5,500	5,500	6,000	6,000
Accumulated Cost	1	12	22	142	352	2,052	4,752	9,352	13,952	19,452	24,952	30,952	36,952

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203[illegible]	Total	
Program Development														
Mission concept developmen														
Phase A design													40	
Phase B design													800	
Phase C build	1,000	1,000											16,000	
Nuclear power development and test	500	500	500	500	500	500	500	500	[illegible]				[illegible]	
Lunar Test Mission														
Transfer habitat assembly at ISS														
Lander assembly	500													
Launch and assemble propulsion elements	1,000	1,000												heet
Final assembly and checkout		500												
Transfer to Lunar orbit			500											
Lunar surface exploration, 2025				500	Lunar Landing in 2025									
Return to Earth orbit					500									
Lunar Program Cost													42,052	
Mars Mission 1													0	
Refurbish transfer habitat for Mars mission						500							500	Refurbish transfer habitat at ISS
Phase C build	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000				10,000	
Launch and assemble propulsion elements	2,000	3,000	5,000	5,000	5,000	4,000	4,000	4,000	4,000				40,000	$40.3 B launch cost from Mars Mission Launch Cost workshe
Attach transfer habitat to ISS and refurbish						500							500	
Assembly landers							500	500					1,000	
Final assembly and checkout									500				500	
Transfer to Mars orbit										500			500	180 day transfer mission
Mars surface exploration, 2032									Mars Landing in 2032		500		500	540 day surface mission
Return to Earth orbit												500	500	180 day return mission
Mars Program Cost													54,000	
Cost per Year	6,000	7,000	7,000	7,000	7,000	6,500	6,000	6,000	6,000	500	500	500		
Accumulated Cost	42,952	49,952	56,952	63,952	70,952	77,452	83,452	89,452	95,452	95,952	96,452	96,952		

Lunar Landing
2025 / $43 B

Mars Landing
2032 / $54 B

All calculations are based on the author's interpretation of the formulas, data, and rules of thumb found in the text, "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke. This presentation is for educational purposes only.

ISS Mission Program Summary

- The following program calculations do not include ongoing crew flights to the ISS for support of the ISS, Lunar and Mars programs

- ISS Program
  - Ongoing crew flights to ISS per year
    - 4 Ares 1
    - 2 Soyuz
    - 2 Proton M
- Launch Cost:
  - Assume equivalent of 8 Delta IV launches: $1.3 B

Lunar Missions Program Summary

- Vehicle Development
  - 2009-2010 Pre-Phase A studies
  - 2010-2013 Phase A designs
  - 2012-2017 Phase B designs
  - 2014-2023 Phase C build
  - 2012-2023 launch & assembly
    - 52 launches
    - Launch Cost: $13.8 B
- Lunar Test Mission
  - 2024 transfer to lunar orbit
  - 2025 lunar surface mission
  - 2026 return to earth orbit
- Program Cost: $43 B
- $4.5 B peak in annual cost
- Recurring Lunar Crew Missions after 2026
  - 9 launches
    - 1 Delta IV Heavy
    - 4 Delta V Tankers
    - 1 Delta V Dbl Tanker
  - Launch Cost: $1.7 B
- Recurring Lunar Cargo Missions (1 Cargo Mission will support Reusable Landers for 3 to 4 Crew Missions)
  - 9 launches
    - 4 Delta IV Heavy
    - 4 Delta V Tankers
    - 1 Delta V Dbl Tanker
  - Launch Cost: $1.9 B

Mars Missions Program Summary

- Vehicle Development
  - 2021-2030 Phase C build
  - 2018-2030 launch & assembly
    - 139 launches
    - Launch Cost: $40.3 B
- Mars Mission
  - 2031 transfer to Mars orbit
  - 2032 Mars surface mission
  - 2033 return to earth orbit
- Program Cost: $54 B
- $6 B peak in annual cost
- $7 B peak in annual cost when overlapped with Lunar Test Mission phasing

- Recurring Mars Missions
  - After the 3rd Mars Mission a propellant depot capability is established to provide propellant for reusable Landers and return and reuse of the Transfer Habitat
  - 44 launches
    - 1 Delta IV Heavy
    - 33 Delta V Tankers
    - 10 Delta V Dbl Tankers
  - Launch Cost: $13.1 B

Program Summary

- Development Cost: $34.6 B
  - Lunar Test Mission: $16 B
  - Mars Mission: $10 B
  - Nuclear Power: $8.6 B
  - Schedule: 2014-2030 (16 years)
    - $1 B to $2.5 B per year
- Launch Cost: $54.1 B
  - Lunar Test Mission: $13.8 B
    - 52 launches
  - Mars Mission: $40.3 B
    - 139 launches
  - Schedule: 2016-2030 (14 years)
    - 191 launches total
    - About 8 to 20 launches per year from all International Partners
- ISS Program Cost: $36.8 B
  - Phase C Support: $16 B
  - Launch Cost: $20.8 B
  - Schedule: 2014-2030 (16 years)
    - 128 launches
    - About 8 launches per year from all International Partners
- Total Lunar and Mars Program Cost: $133.8 B
  - Lunar Test Mission: $43 B
  - Mars Mission: $54 B
  - ISS Support: 36.8 B

Findings

- Transportation
  - Large propellant requirements supports logic for large heavy lift launch vehicles
    - Saturn V
    - Ares V
  - Launch cost of all elements for the Lunar and Mars missions is $54.1 B, of which $49 B is for the propellant and propellant stages.
    - What is the development cost for the Ares V?
    - How many Ares V launchers can be produced for $50 B?
  - Use of existing launch systems supports growth of commercial markets
  - Lunar Missions with in-space assembly appears feasible with current launch systems, (i.e., Delta-IV Heavy, Proton M, and Ariane 5)
  - Saving the return habitat does not appear feasible for initial Mars missions due to large propellant requirements

Findings

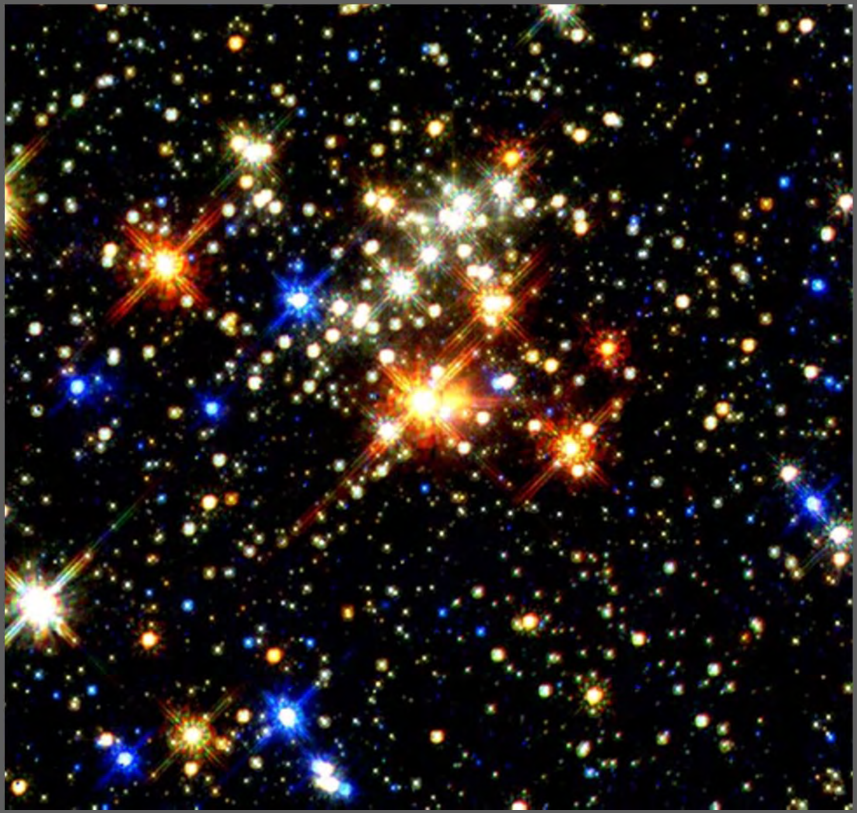
- Mission Design
  - One design for both lunar and Mars missions saves program development time and cost
  - Reusable Lunar Landers and Reusable Mars Landers can be about the same size and mass
  - Propellant production at Mars for return missions reduces vehicle size and makes saving the return habitat more feasible
  - Propellant Storage depots look more attractive in Earth – Moon neighborhood, whereas Propellant Production depots look attractive at Mars
- Nuclear Systems
  - Nuclear surface power is included for Mars development due to difficulty solar systems would have on the surface
  - Nuclear propulsion was not selected because the large hydrogen tank mass negated the advantages of the high engine efficiency

Technology Issues

- In-space alignment and docking of large mass vehicles
- Water resource acquisition on Mars
- Propellant production in space and on the surface of Mars
- Long term storage of propellants in space
- Delta V vehicle configuration feasibility
- Reuse of engines for Lander and propellant stages
- Surface nuclear power on Mars
- Precision Landing, especially on Mars where the landing system is dependant on parachutes
- ISS operations
  - Re-boost operations as center of mass shifts
  - Additional power requirements for attached elements
  - Support vehicle and payload delivery docking and berthing operations

. . . and a special thanks to all that encouraged, inspired, and supported this effort . . .

- NASA Marshall management, and the Full Time Study Program
- University of Houston, Sasakawa International Center for Space Architecture
- Prof. Larry Bell, Assist. Prof. Olga Bennova, Harmon Everett, Prof. Peter Noldt
- Kriss Kennedy, Joe Howell, Jim Talbot, Larry Toups, Reggie Alexander
- Rachel Smitherman, Ana Mari Cadilla, Margaret Smitherman



Acronyms and Abbreviations

B	Billion
dbl	double
dia.	Diameter
ESA	European Space Agency
EVA	Extra-Vehicular Activity
g	gravity
ht.	height
in.	inches
ISS	International Space Station
kg	kilograms
kW	kilowatts
LEO	Low-Earth-Orbit
m	meters
M	Million
TLI	Trans Lunar Injection
TMI	Trans Mars Injection
US	United States

Reference Materials

A Comparison of Transportation Systems for Human Missions to Mars, by Griffin, B., et al, AIAA Technical Paper

Encyclopedia Astronautica website, http://www.astronautix.com

Human Space Flight: Mission Analysis and Design, edited by Willey J. Larson and Linda K. Pranke, Space Technology Series, McGraw-Hill Companies, Inc.

International Space Reference Guide to Space Launch Systems, Third Edition, Steven J. Isakowitz, Joseph P. Hopkins Jr., Joshua B. Hopkins, AIAA, 1999

National Aeronautics and Space Administration website: http://www.nasa.gov

Sasakawa International Center for Space Architecture (SICSA) website: http://www.sicsa.uh.edu

Space Solar Power and Platform Technologies for In-Space Propellant Depots, Final Report, November 14, 2000, Boeing Company in cooperation with NASA Marshall Space Flight Center, NAS8-99140, Mod.2, Task 3

AIAA Technical Papers by Smitherman, D. et al

Spreadsheet Analysis

- ARCH 6398: Special Projects
  - Detailed Spreadsheet analysis of launch vehicles, lunar test mission, and Mars mission
    - Surface Base Sizing Tool
    - Habitat Sizing Tool
    - Crew Accommodations Sizing
    - Surface Habitat Outfitting
    - Transfer Habitat Outfitting
    - Crew Consumables Data
    - Surface Payloads Mass Summary
    - Lunar Lander Sizing
    - Mars Lander Sizing
    - Excursion Vehicle Sizing
    - Lunar Vehicle – Chemical Staging
    - Lunar Cargo Missions
    - Lunar Crew Missions

- Recurring Lunar Cargo Missions
- Recurring Lunar Crew Missions
- Mars Vehicle – Chemical Staging
- Mars Crew & Cargo Missions
- Mars with Operational Depot
- Recurring Mars Missions
- Mars Transfer Habitat Mass
- Crew Return Vehicle Sizing
- Propellant Depot Sizing
- Vehicle Configurations
- Launch Vehicle Sizing
- Launch Vehicle Options
- Lunar Test Launch Cost
- Mars Mission Launch Cost
- Program Plans
- Tanks Sizing Tool

(Continued)

Spreadsheet Analysis

(Continued)

- Water Wall Sizing Tool
- EVA Systems Data
- Lander Ref. Data
- Power Production Sizing Data
- Power Requirements Data
- Robotic Systems Data
- Ref. Mars Habitat Lander
- Artificial Gravity Data
- Greenhouse Sizing Tool
- Delta-v Data
- Engine ISP Data
- Systems Sizing Data

- 41 Excel Spreadsheets were generated to size everything from launch vehicles to crew accommodations. All formulas, data and rules of thumb are based on the text "Human Spaceflight: Mission Analysis and Design" by Larson & Pranke
- File Name: LunarMarsSizing081208.xls contains the 41 workbooks listed. Many workbooks are linked where indicated.

Design Animations

ARCH 7610: Master's Project – Space Architecture

- Conceptual Design and Animations using 3-D computer modeling; AutoDesk 3D Studio Max, Versions 9 and 2008
  - Delta IV Heavy Launch
  - Delta V Tank Launch
  - Delta V Double Tank Launch
  - Delta V Lander Launch
  - Assembly Operation At ISS
  - Transfer Vehicle Tether Assembly
  - Transfer Vehicle TMI
  - Artificial Gravity Phase
  - Lunar and Mars Orbit Operations
  - Lander 1 Deployment
  - Lander 2 Deployment
  - Lander 3 Deployment
  - Lander 4 Lunar Solar Power
  - Lander 4 Mars Nuclear Power
  - Surface Habitat Assembly
  - Module Assembly Details
  - Habitat Tour
  - Habitat Configurations
  - Electromagnetic Water Launcher

Moon to Mars Mission Assumptions

Appendix A

ISS Utilization

Assumptions	Notes
Design to make innovative use of exiting space technology (including ISS) where practical.	Modules, racks, docking devices, power systems, etc., to be compatible with ISS systems.
The ISS is to be transferred to a lower inclination and used as the Mars Ship assembly platform after its current mission. (Optional)	Attachment will be made through the Node 1 (nadir / zenith) port.
ISS to be operated as a port authority for both commercial and government activities.	Commercial activities at space station to be permitted.
Assembly will be done one module or component at a time as done with space station.	Assume about 4 crew flights per year (Ares I and/or Soyuz), 2 servicing flights per year (Progress or others), and 8 cargo flights per year (Delta IV and others); two major assembly operations per crew rotation.

Power and Propulsion

Assumptions	Notes
Assume abundant power from nuclear systems with options and back up using solar power	Include Thermal Nuclear Generators and Radiant Thermal Generator systems. Provide adequate protection using water shielding as needed.
Existing commercial launch systems to be utilized to the greatest extent possible.	Delta IV Heavy is used as a baseline, but capable launch systems include Ariane, Proton, Titan
Delta IV Heavy to be baseline system for all propulsive stages for vehicle transfer to and from Mars	Other vehicles, Titan, Progress, and Aerean are options
Assume no heavy lift vehicle will be built.	No Saturn V or Ares V vehicles to be developed.

Water

Assumptions	Notes
An abundant propellant option is assumed utilizing water converted to propellants at a servicing platform at or near the Mars Ship assembly area.	Propellant depot to be operational for commercial and exploration missions Mars surface water to be exploited for long term habitation
Assume mission options for use of water produced at Mars	Options include additional EVAs, propellants to support reusable landers, and propellants to support de-acceleration of transfer habitat into LEO
SPE and GCR radiation protection to be provided per current knowledge with options for additional protection as more is understood.	Design for 15cm water jacket around all habitat areas. Carry 5-10cm equivalent of water with remainder provided at Mars or on later missions.
Carry minimal water for habitat and nuclear power source.	Assume options for adding water to habitat and nuclear power shielding from Martian sources to increase overall radiation protection over time
All water, propellant and oxygen to be provided for entire mission. Electrolysis equipment will be provided to convert excess water to oxygen and propellants	Surface water will be utilized to provide extra EVA operations and extra propellants for transit to other exploration site options

Reusable Systems

Assumptions	Notes
Propellant production from water to be the baseline through entire mission.	Assume water deliveries to LEO for Mars Ship propellant production. Water deliveris to Mars orbit, and Mars surface water extraction.
First mission to deliver a water based propellant production capability to Mars orbit and the surface outpost.	Required for more efficient operation of future missions.
Mars landers to be refueled at Mars orbit and surface propellant production facilities.	Assume two landers as hopers with ruse capabilities, and the other two landers used for crew ascent only at end of mission
Landers may be used as hoppers for transport to exploration sites around the planet.	Refueling to be done at surface depots or on orbit.

EVA

Assumptions	Notes
Assume options for an EVA extensive mission design	Assume option abundant water and use of existing surface water resources to support extensive EVA operations
Design for maintenance and repair of all systems	Provide materials and equipment designed to fabricate replacement parts as needed
Provide at least two airlocks to overall habitat and two access hatches to all habitable volumes	One access hatch can be from outside with emergency pressure balls on inside for stranded crew
Provide two EVA suites for each crew member	Suits to be modular in design for repair capability

Mobility

Assumptions	Notes
All mobile systems to accommodate two driving stations and remote driving operations from habitat	Remote operations to be possible from any crew location via laptop
Surface habitats to be movable but not necessarily a mobile habitat design	Mobility options to include relocation of habitats, pressurized rovers, un-pressurized rovers, pressurized hoppers, and EVA
All mobile systems carry 8 crew in an emergency and at least 2 crew under normal operations	Provide vehicle accommodation for injured crew

Design / Operation

Assumptions	Notes
Full duration test mission will be run to the Moon and back prior to Mars mission	Mars Ship will be refurbished or new ship constructed during lunar test mission
Lunar Test Mission will leave similar assets in place to support future science and commercial operations.	(Reusable landers and propellant production and storage systems.)
Assume dust problems on Mars may be similar to lunar dust problems	Mars should not be as bad, but same precautions are needed
Distribute supplies in all habitable volumes for emergency access and use	Provide EVA access to all habitable volumes for emergency access
Some systems and supplies may be sent ahead of time prior to crew arrival	Extra water, propellants, supplies, and habitable volumes may be sent ahead of time if mission scenario seems practical
Habitat has near 100% water, closed loop system	Human waste products my be used in greenhouse systems
Create redundant habitable volumes that can accommodate all crew in emergency situations	Design life support supplies for rescue time required in the event system failure occurs at the return phase. (3 years?)

Mars Mission Elements

Appendix B

A breakdown of all the major vehicle and infrastructure elements required to create and support the Mars Ship.

Mars Mission Elements

- Mars Ship Elements
- Mars Transfer Vehicle
  - Transfer Habitat w/ Science Facilities
  - Propulsion Systems
  - Propellant production
  - Exploration vehicle (Phobos / Deimos)
  - Crew return vehicles
- Mars Surface Vehicles
  - Landing vehicles
  - Habitat w/ Science Facilities
  - Surface Mobility
  - Surface / Sub-surface exploration
  - Propellant production

- Infrastructure Elements
- ISS
  - Supports 6 crew
  - Growth to 12 crew as Mars Ship habitats are added
  - Gradually moved to lower inclination orbit with each re-boost operation
  - Operated as a port authority for government and commercial operations
- Propellant Production
  - Attached to ISS, Mars Ship, or free-flyer
  - Water storage
  - Propellant production and storage
  - Transfer and servicing vehicles, crew and remote operated
  - All commercial operations
- Orbital Systems
  - Global communications, navigation, mapping, weather satellites

Crew

- 8 Crew Members
  - 2 Pilots / Systems Specialists
  - 2 Medical Doctors / Life Sciences Specialists
  - 2 Geologists / Materials Sciences Specialists
  - 2 Astrophysicists / Space Science Specialists

- Mission scenario
  - 6 crew members will go to surface in two landers
  - Two landers will be landed autonomously, or by remote operations
  - 2 crew members will explore Phobos and Deimos with options to go to surface later using a reusable lander

- Lunar mission will be a test run for long duration, mixed gender crew, single and married couples.

Mars Transfer Vehicle Habitats

- Habitable Areas
- Habitat
  - Mission Control Center
    - Vehicle guidance, navigation & control center
    - Communications
    - Remote operations control center
  - Galley
    - Food storage
    - Meal preparation
    - Dining
  - Crew quarters
    - Sleeping bunk
    - Work desk
    - Personal storage
  - Restroom Facilities
    - Toilet
    - Shower
    - Sink
  - Laundry
- Science Facilities
  - Life Sciences Facility
    - Medical equipment
    - Exercise equipment
  - Greenhouse
    - Food production
    - Waste recycling
    - Oxygen generation
  - Geo Sciences Facility
    - Materials research
    - Materials storage
    - Fabrication equipment
  - Space Sciences Facility
    - Telescopes and detectors
    - Environmental detection equipment
  - Extravehicular Activity (EVA) Facility
    - Pressure suit maintenance
    - Storage
    - Airlock

Mars Transfer Vehicle Systems

- Non-Habitable Systems
- Environmental Control & Life Support
  - Air quality control
  - Temperature control
  - Water reclamation & purification
- Communications
  - Voice, video, and data handling
  - Data storage
- Guidance, Navigation & Control
  - Star trackers
  - Control moment gyros
  - Thrusters
- Power
  - Nuclear Thermal Generators
  - Solar Arrays
  - Radiators
- Propulsion Systems
  - Propellant storage
  - Engines
- Propellant Production
  - Water storage
  - Electrolysis system
  - Propellant storage
  - Transfer systems
- Structures
  - Habitat pressure vessels
  - Propellant pressure vessels
  - Primary structures
  - Movable structures
- Thermal Control
  - Insulation systems
  - Heaters
  - Radiators
- Environmental Protection
  - Micrometeoroid debris shield
  - Solar Particle Event (SPE) protection
  - Galactic Cosmic Ray (GCR) protection

Mars Surface Vehicles

- Landing Vehicles
- Descent/Accent Vehicle Control Center
  - Vehicle guidance, navigation & control center
  - Communications
  - Remote operations control center
- Crew Accommodations
- Environmental Control & Life Support
  - Air quality control
  - Temperature control
  - Water storage
- Communications
  - Voice, video, and data handling
  - Data storage
- Guidance, Navigation & Control
  - Star trackers
  - Thrusters
- Power
  - Nuclear Thermal Generators
  - Radiators
- Propulsion Systems
  - Propellant storage
  - Thrusters
  - Main engines
- Environmental Protection
  - Micrometeoroid debris shield
  - Solar Particle Event (SPE) protection
- Structures
  - Assent/Descent module pressure vessels
  - Propellant pressure vessels
  - Primary structures
  - Movable structures
- Thermal Control
  - Insulation systems
  - Heaters
  - Radiators

Mars Surface Habitat

- Habitable Areas
- Habitat
  - Mission Control Center
    - Vehicle guidance, navigation & control center
    - Communications
    - Remote operations control center
  - Galley
    - Food storage
    - Meal preparation
    - Dining
  - Crew quarters
    - Sleeping bunk
    - Work desk
    - Personal storage
  - Restroom Facilities
    - Toilet
    - Shower
    - Sink
  - Laundry
- Science Facilities
  - Life Sciences Facility
    - Medical equipment
    - Exercise equipment
  - Greenhouse
    - Food production
    - Waste recycling
    - Oxygen generation
  - Geo Sciences Facility
    - Materials storage
    - Fabrication equipment
  - Space Sciences Facility
    - Telescopes
    - Environmental detection equipment
  - Extravehicular Activity (EVA) Facility
    - Pressure suit maintenance
    - Storage
    - Airlock

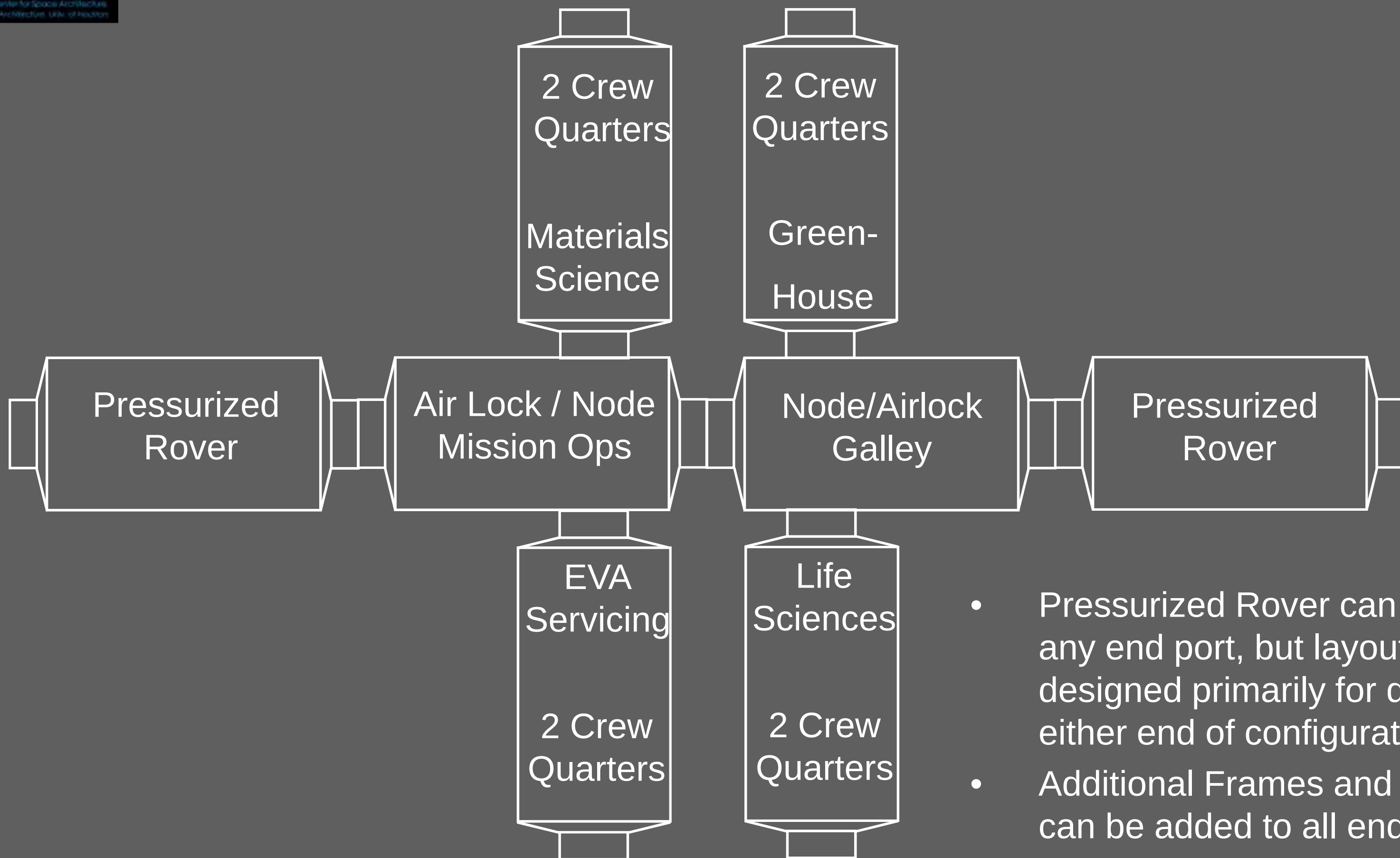
Mars Surface Vehicles & Equipment

- Pressurized Rover
  - Includes all accommodations of a surface habitat module
  - Transports 2-8 crew members
  - Tows un-pressurized rover in its flat-bed trailer configuration
- Un-pressurized Rover
  - Transporting 2-8 crew members
  - Flat-bed trailer configuration for moving large habitat modules
  - Forklift and crane configuration for moving surface equipment
  - Backhoe, and blade attachments for lifting and excavating
  - Drilling rig attachment for subsurface exploration
  - Manual, autonomous, and remote operation modes
- Hopper
  - Two autonomous landers to be refueled and reused as crewed and remote operated hoppers
  - Payload bays available for large payload delivery to and from surface

Habitat Design Drawings

Appendix C

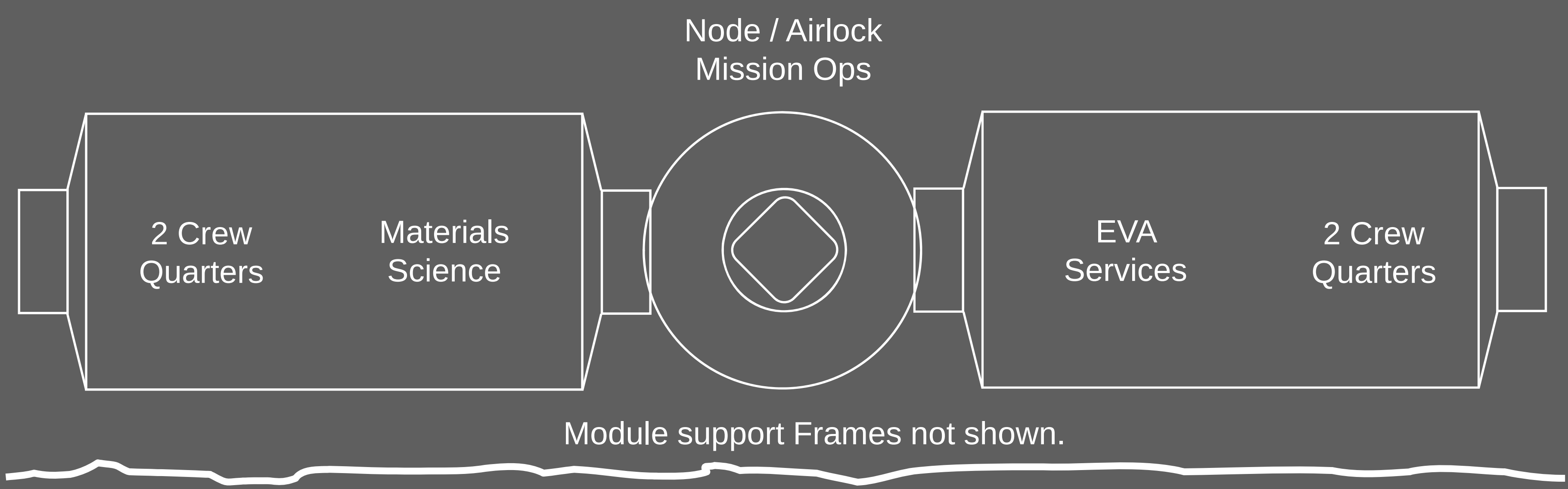
Functional Layout



- Pressurized Rover can dock at any end port, but layout is designed primarily for docking at either end of configuration.
- Additional Frames and Modules can be added to all end ports

Scale: 1/16”=1’-0”

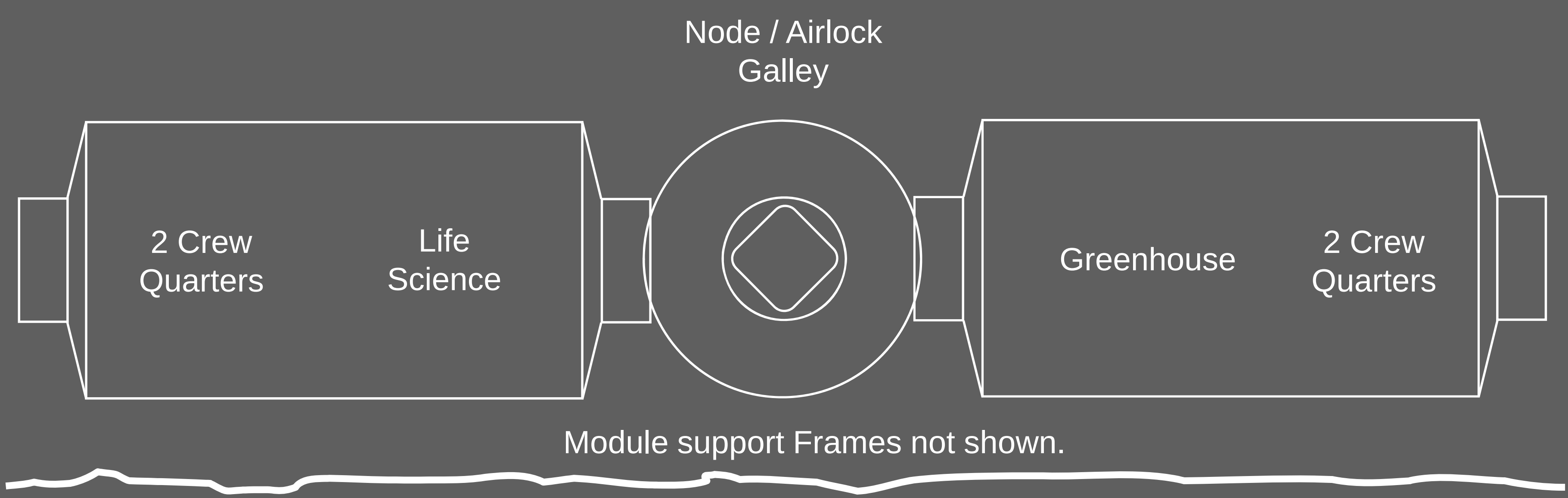
Functional Layout



Module support Frames not shown.

Scale: 1/8”=1’-0”

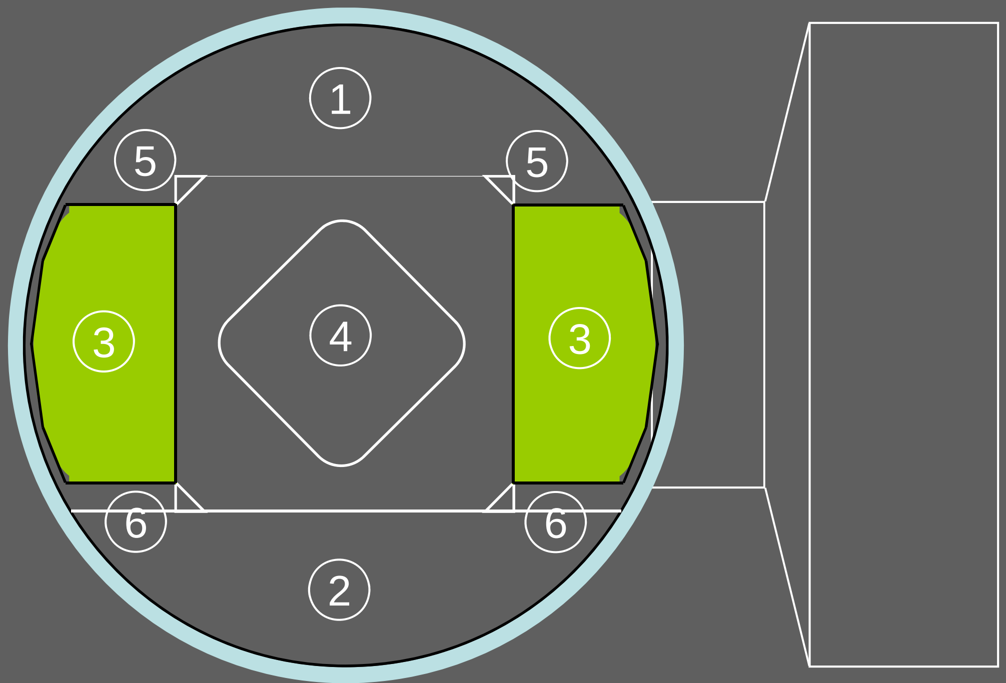
Functional Layout



Module support Frames not shown.

Scale: 1/8”=1’-0”

Standard Module Cross-Section



1. Air systems equipment and distribution
2. Water systems equipment and distribution
3. Standard ISS wall racks
4. Standard ISS hatch turned at 45 degrees for submarine hatch scale
5. Lighting and air supply
6. Air return

Scale: 1/4”=1’-0”

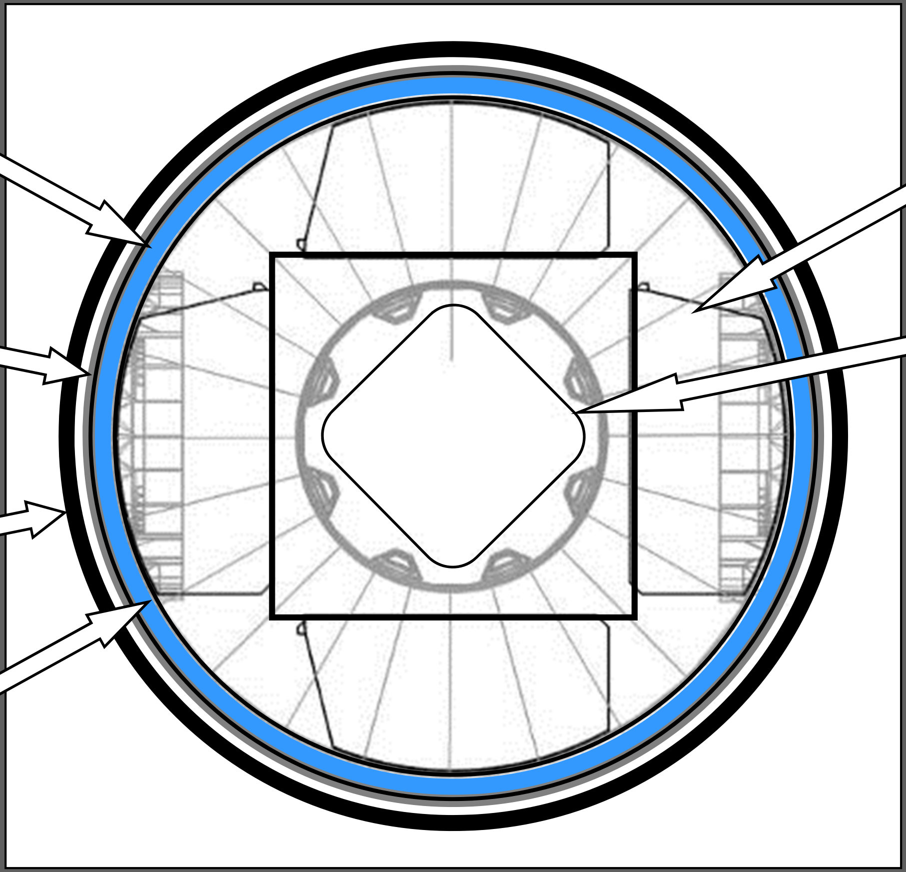
Standard Module Cross-Section

Aluminum pressure shell

Spacers with thermal insulation blankets

Composite debris shield / shroud

Polyethylene water tank liner



Standard ISS racks

Standard ISS docking mechanisms and hatch

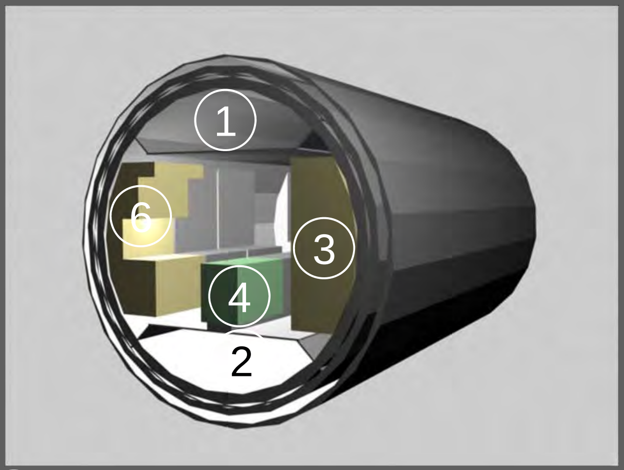
Note: Hatch is turned at 45 degrees to provide more head and foot room for passage in gravity environment.

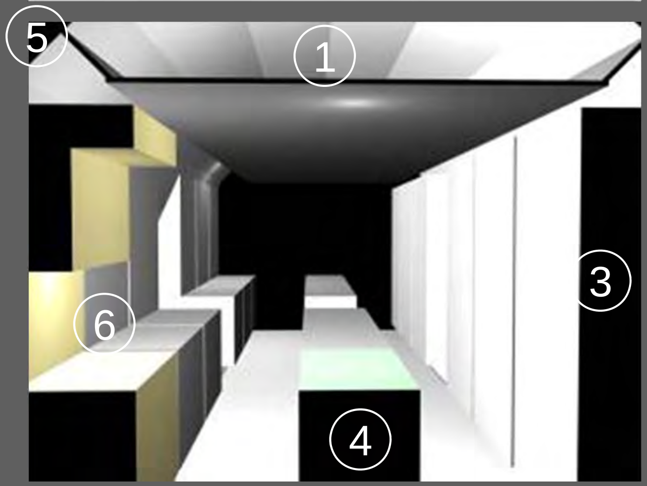
Section: 5m outside dia., 14’ inside dia x 29’ length

Scale: 1/4” = 1’-0”

Interior Design Standards

1. Air systems equipment and distribution
2. Water systems equipment and distribution tied to perimeter water-wall system
3. Standard ISS wall racks
4. Central work counter (ISS interior corridor is about 7x7 feet. This module is slightly larger, 8x8 corridor, which allows space for a center counter where needed.)
5. Lighting and air supply
6. Open work surfaces designed to fit ISS rack standards.

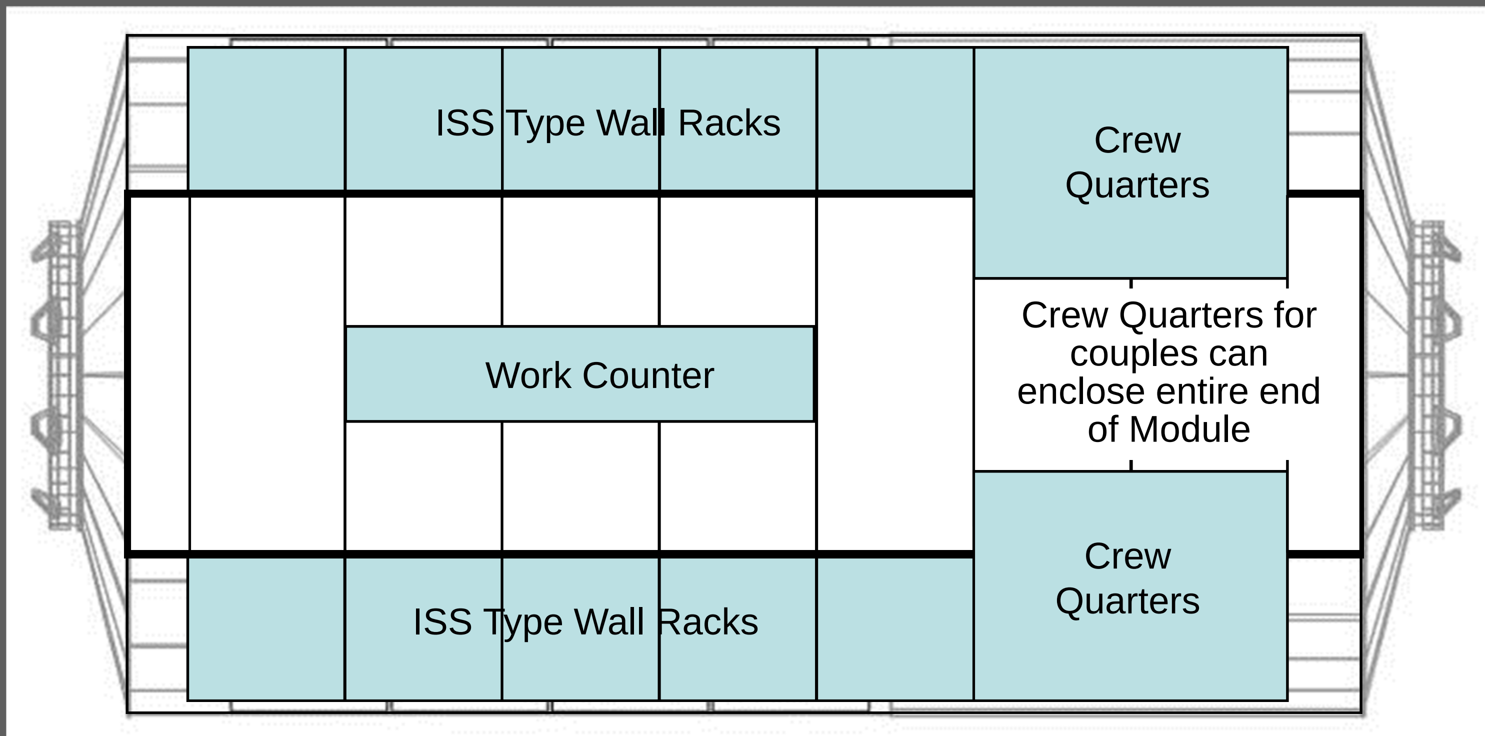




Standard Lab Module Plan

Typical Layout for EVA, Materials Science, Life Science, And Greenhouse Modules

Node



Open Port

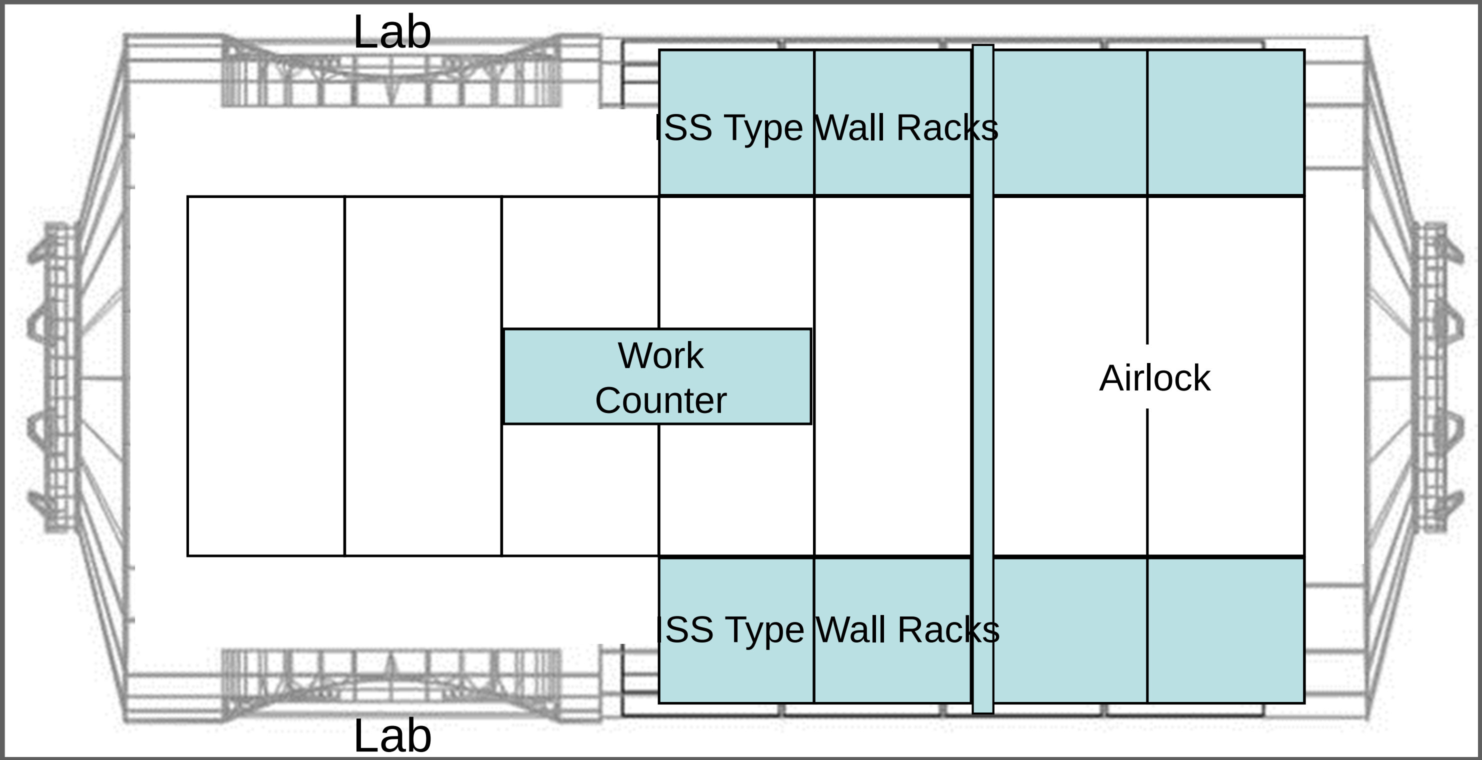
Plan: 5m dia x 9m, 14'inside dia x 29' length; Racks: 1m width

Water wall and debris shield not shown.

Scale: 1/4" = 1'-0"

Standard Node Module Plan

Typical Layout Nodes with Airlocks and either Operations or Galley functions



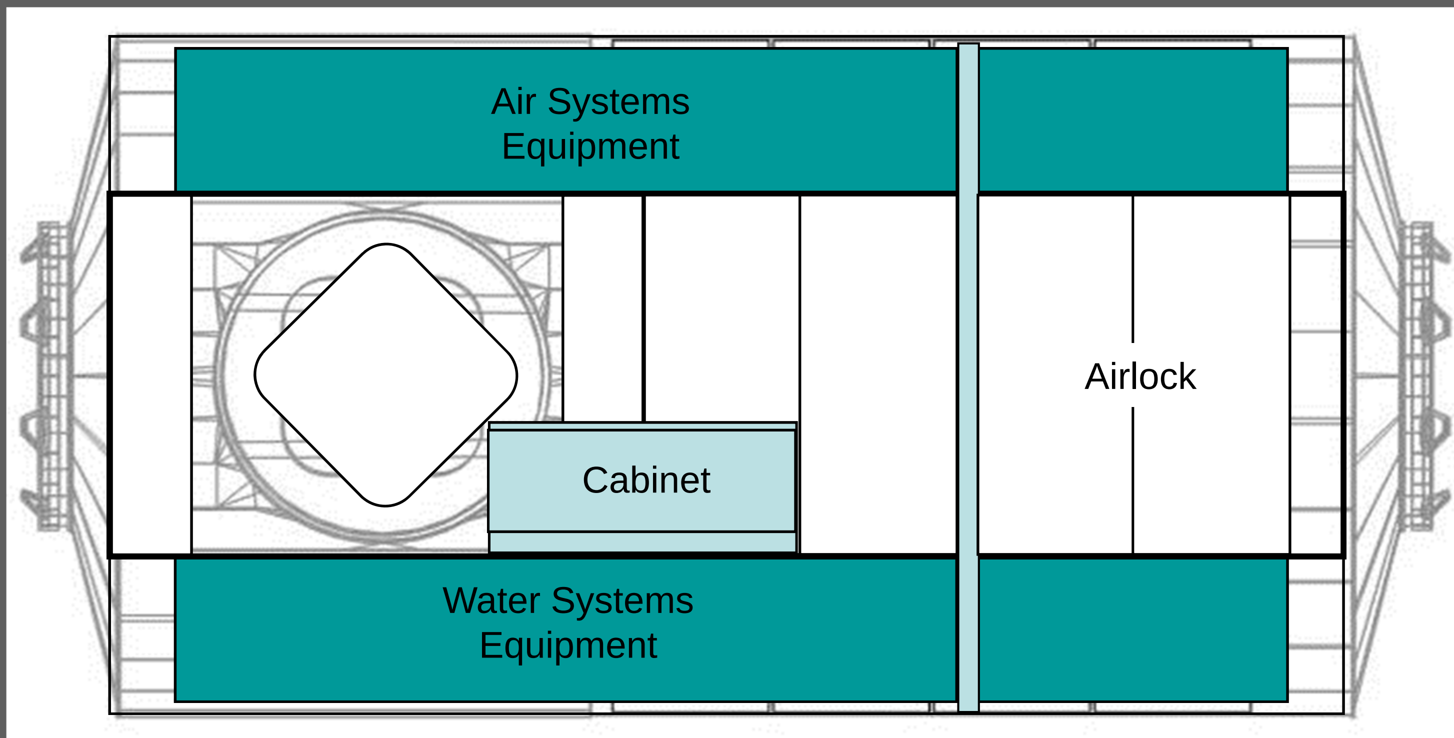
Node

Rover

Plan View: 14'dia x 29' length; Racks: 1m width
Scale: 1/4" = 1'-0"

Standard Node Interior Elevation

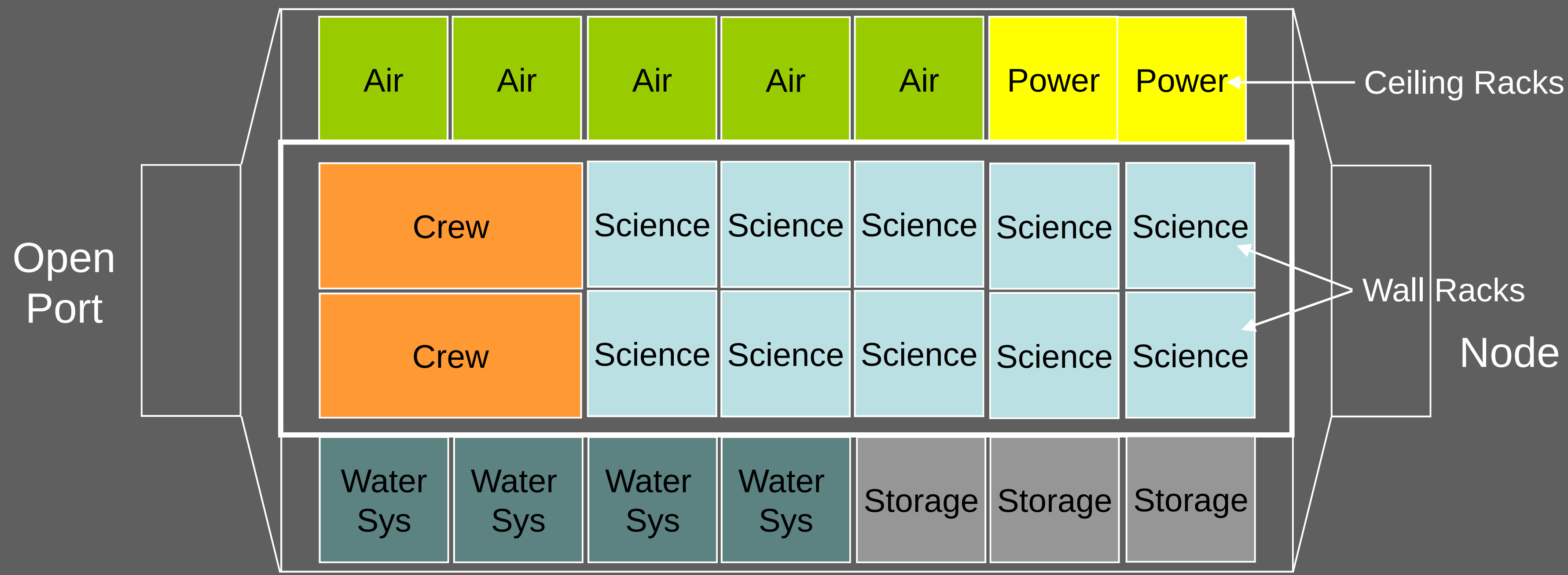
Node



Rover

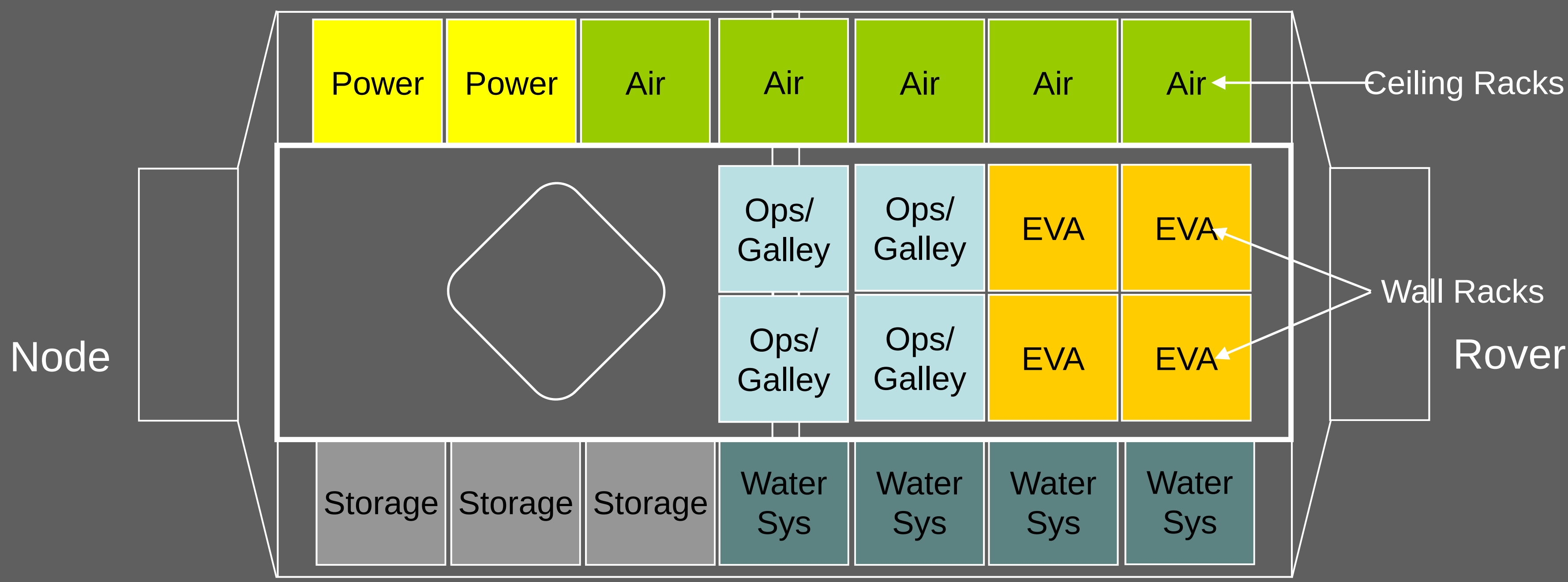
Side Section / Elevation: 5m dia x 9m, 14'inside dia x 29' length
Water wall and debris shield not shown.
Scale: 1/4" = 1'-0"

Materials Science Module



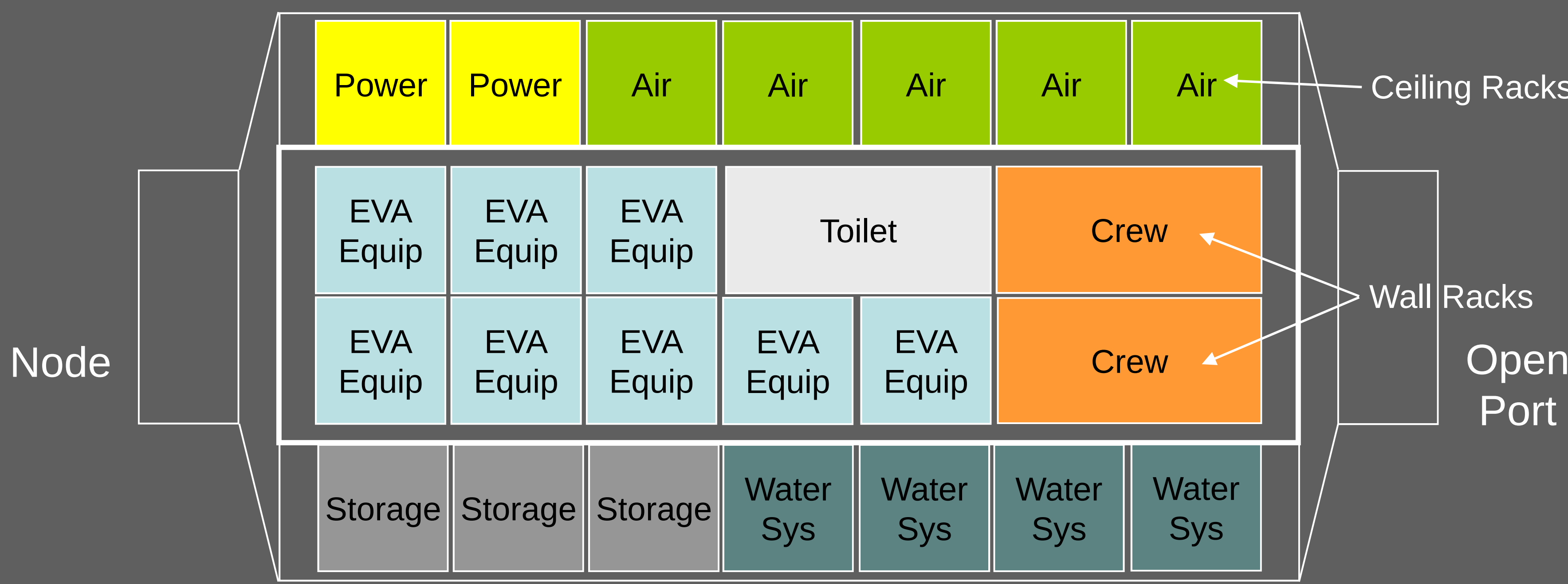
Scale: 1/4”=1’-0”

Node / Airlock Modules



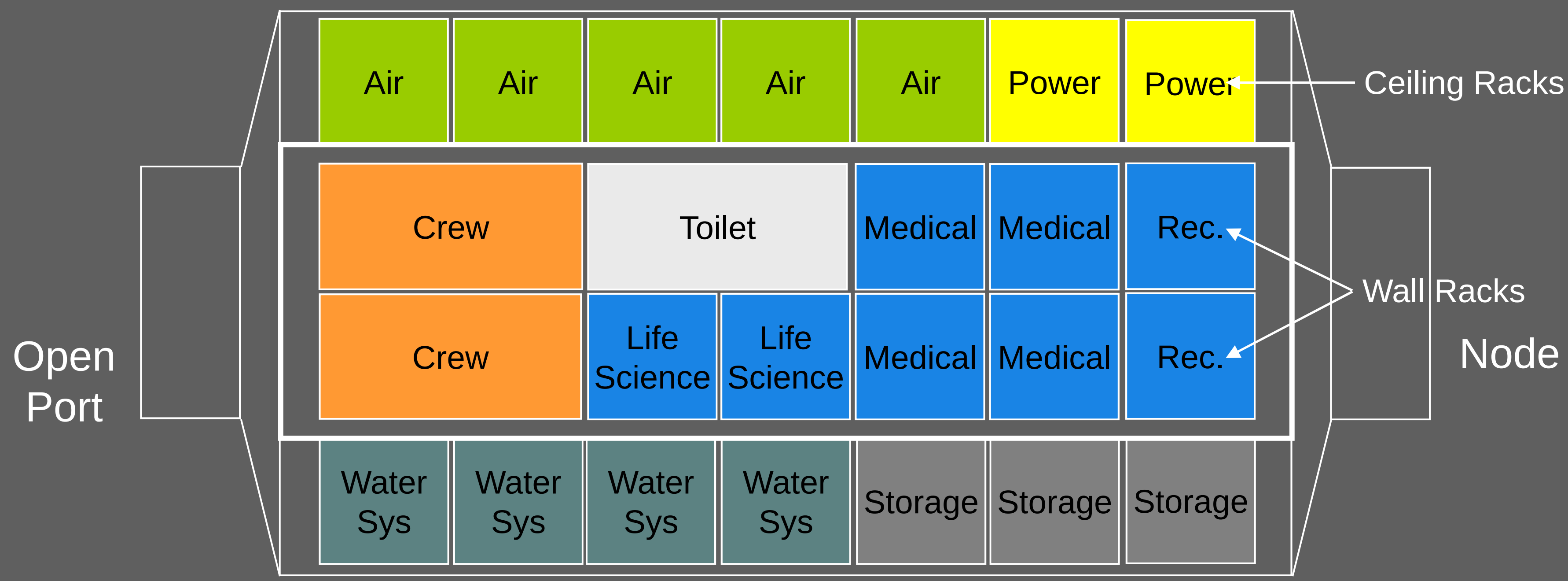
Scale: 1/4"=1'-0"

EVA Equipment Module



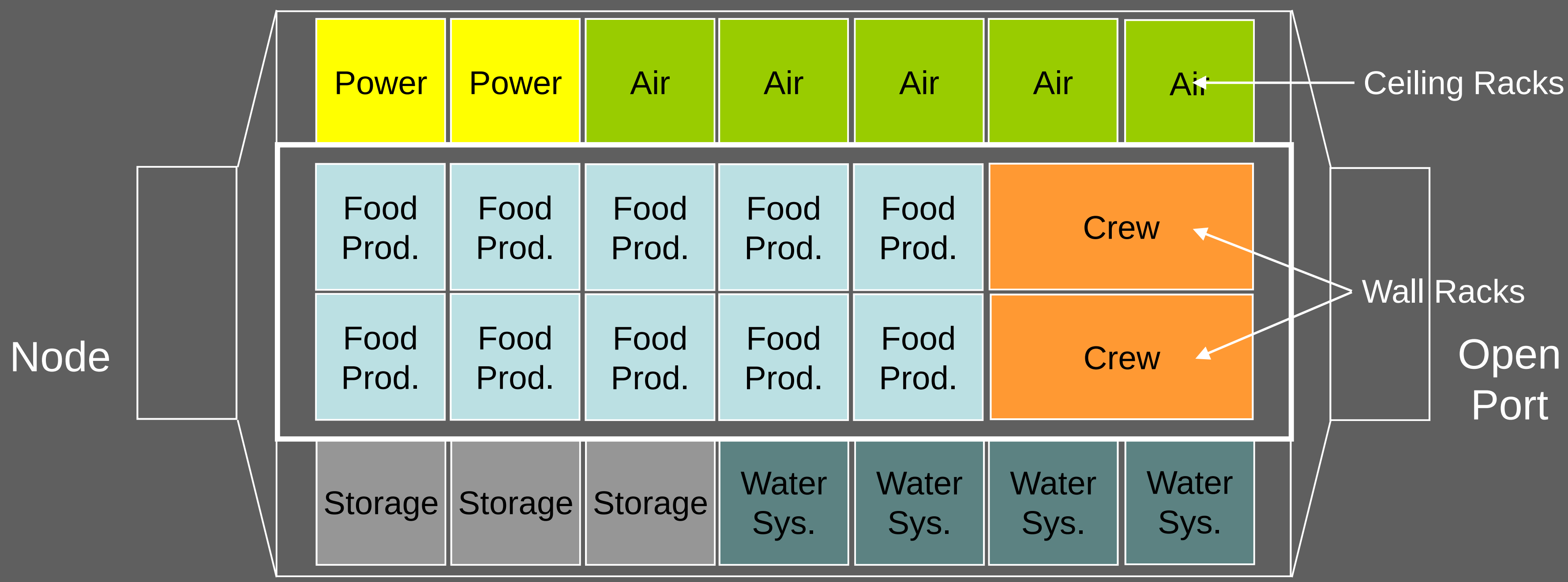
Scale: 1/4"=1'-0"

Life Sciences Module



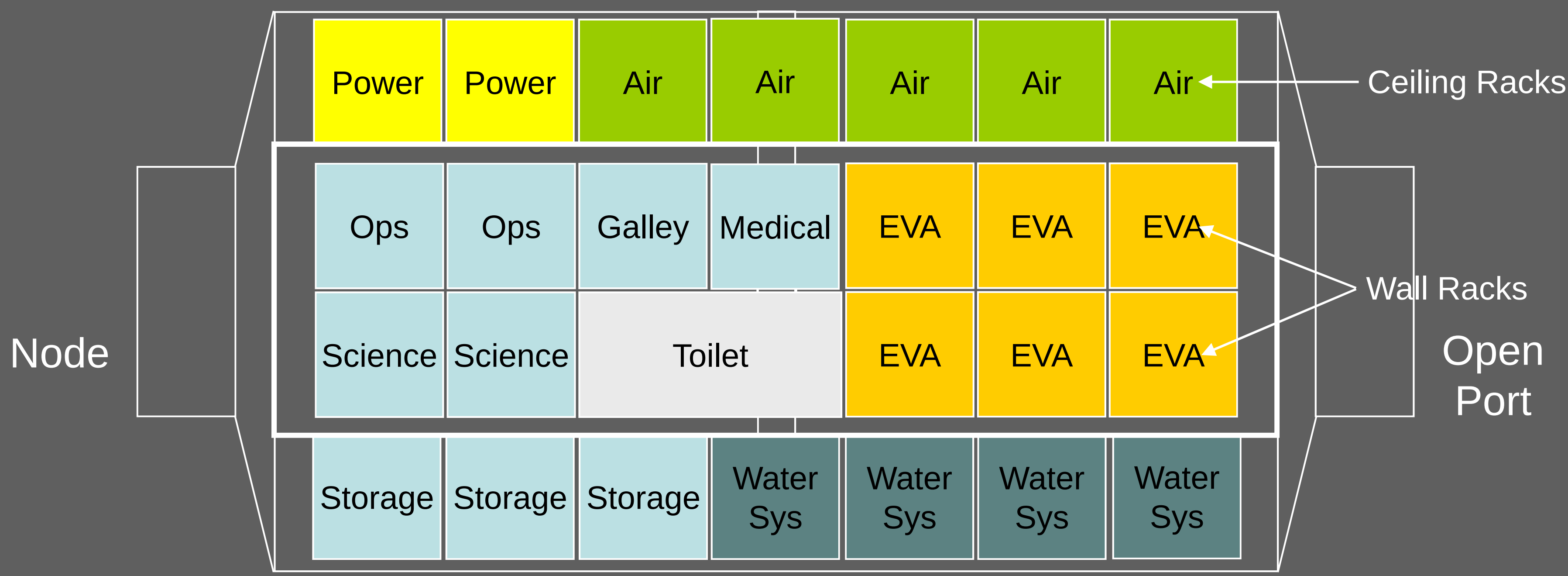
Scale: 1/4”=1’-0”

Greenhouse Module



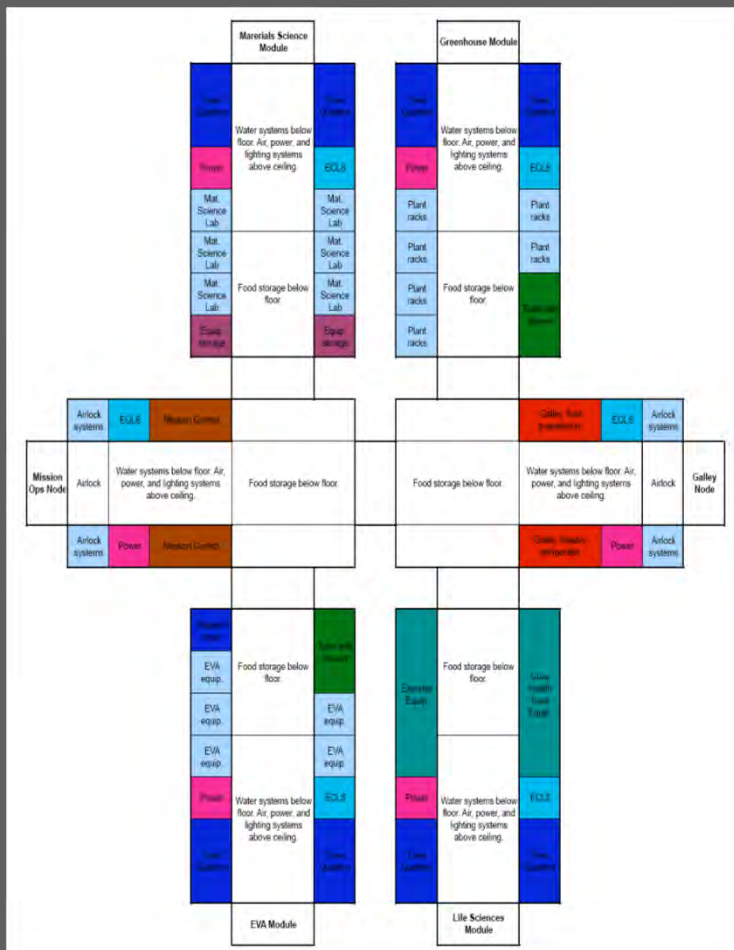
Scale: 1/4”=1’-0”

Pressurized Rover



Scale: 1/4”=1’-0”

Surface Habitat Outfitting

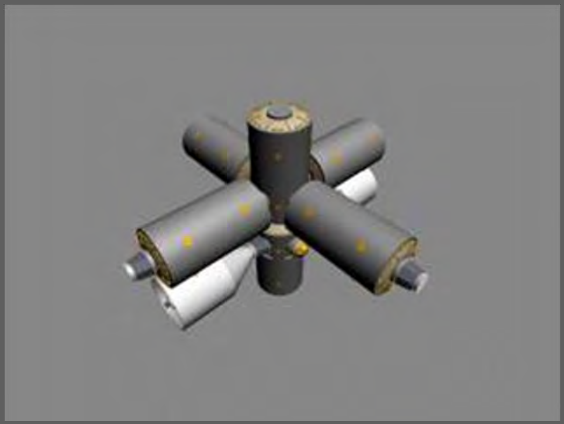


- Crew Accommodations

Transfer Habitat Layouts

- **Single level layout**
- Advantages
  – All laboratory and crew quarters are on the same level
- Disadvantages
  – Two module are perpendicular to the plane of rotation with risk of motion disorders for the crew
- Notes
  – Exploration Vehicle port needs to be added.

- **Multiple level layout**
- Advantages
  – All modules are oriented along the plane of rotation
  – Module layout could be simullar to the surface habitat layout
- Disadvantages
  – More vertical circulation required with crew split on multiple levels

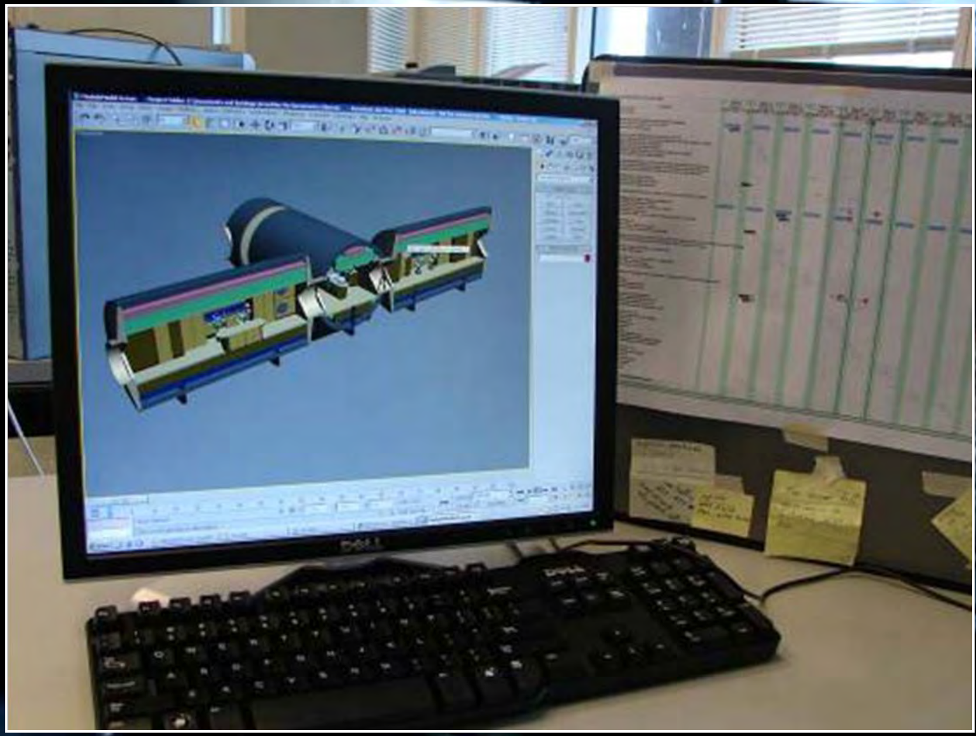


Habitat Module Model

Appendix D

Model Creation

Plastic model created from 3D Studio Max computer file

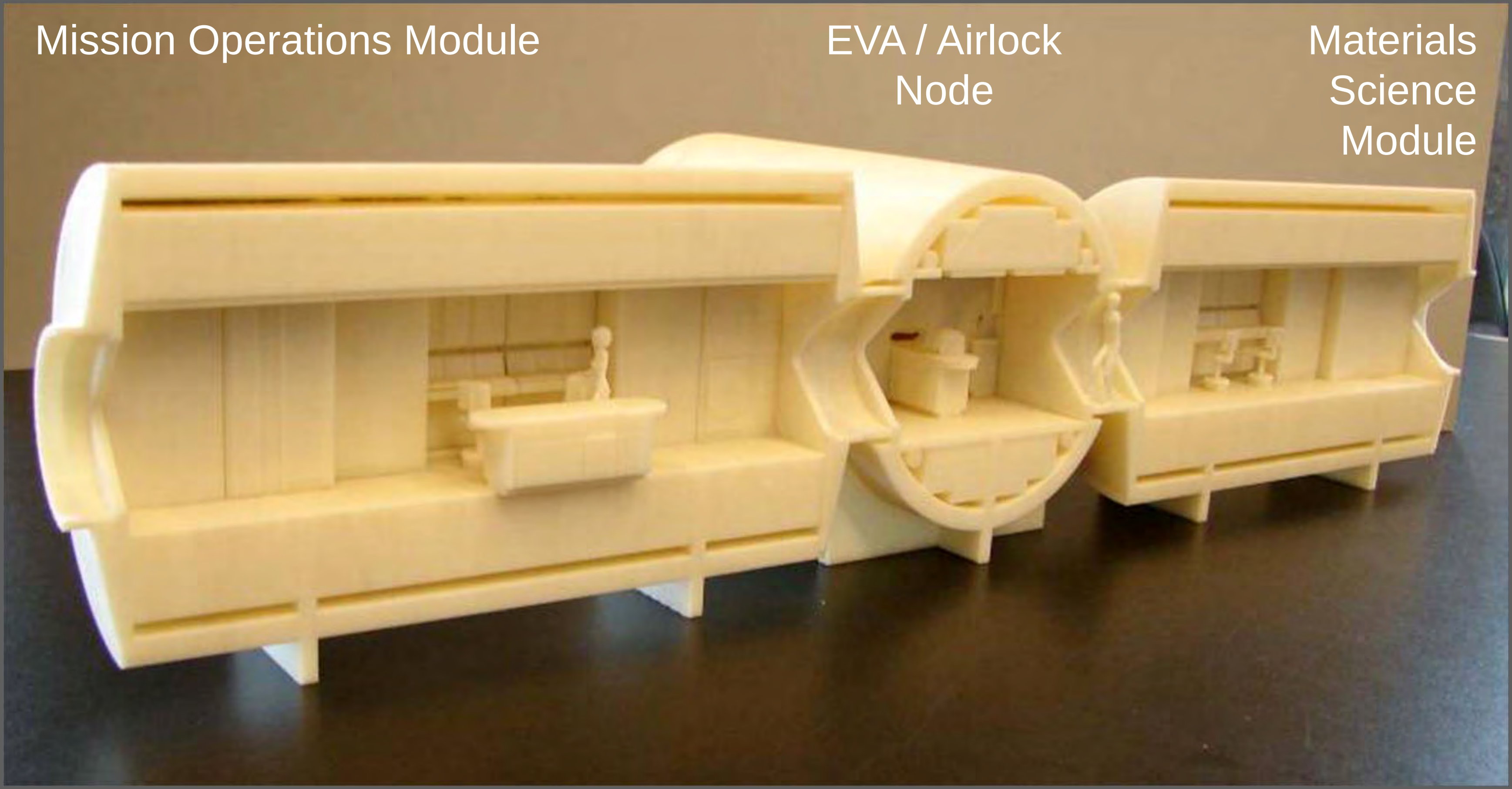


Model Production Equipment

Equipment

- Dimension SST 1200 es 3D printer
- ABS Plastic spools
- Support material bath

Plastic Model



Future Launch and Propulsion Systems

Appendix E

Delta IV Heavy

- Various configurations of the Delta IV Heavy were explored by Boeing in the propellant depot study referenced below. This work generated the concepts for the tanker and double tanker concepts used in this design
- Space Solar Power and Platform Technologies for In-Space Propellant Depots, Final Report, November 14, 2000, Boeing Company in cooperation with NASA Marshall Space Flight Center, NAS8-99140, Mod.2, Task 3

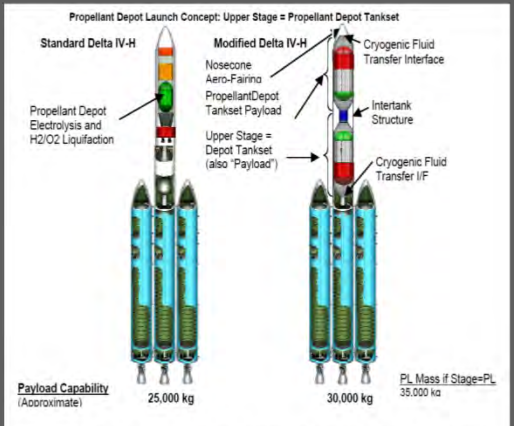
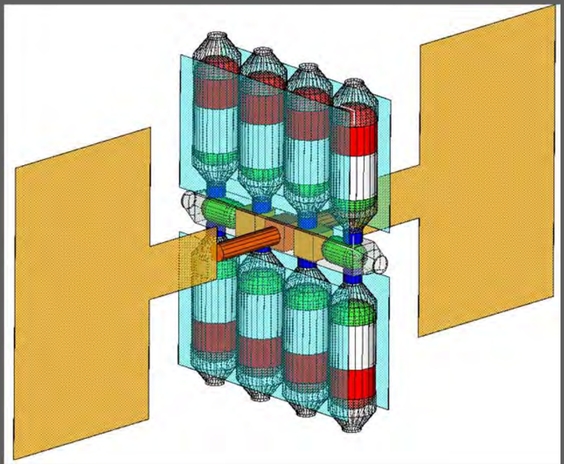


Figure 1-2. Propellant Production Depot tank-sets launch in place of a Delta IV upper stage.



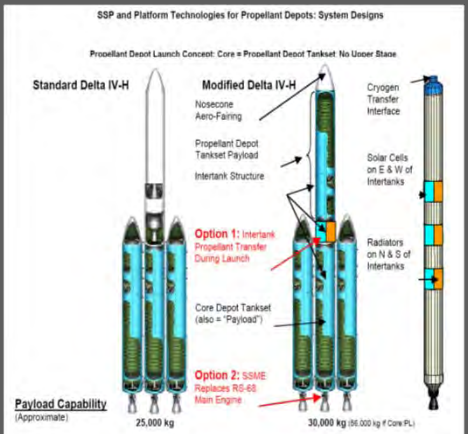


Figure 1-3. Cryogen Storage-Only Depot tank-sets launch in place of the Delta IV core tanks.

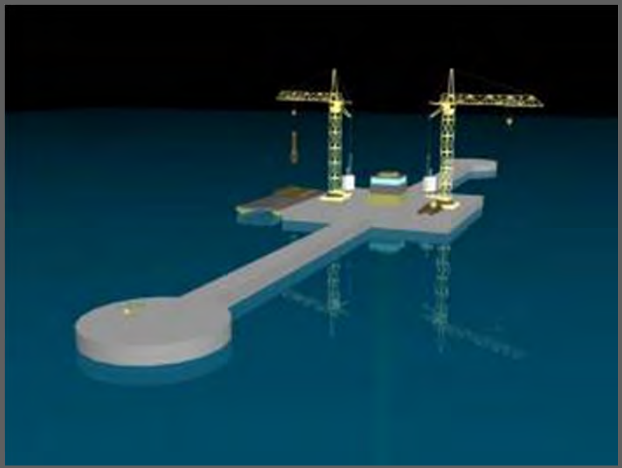
Electromagnetic Launch Systems

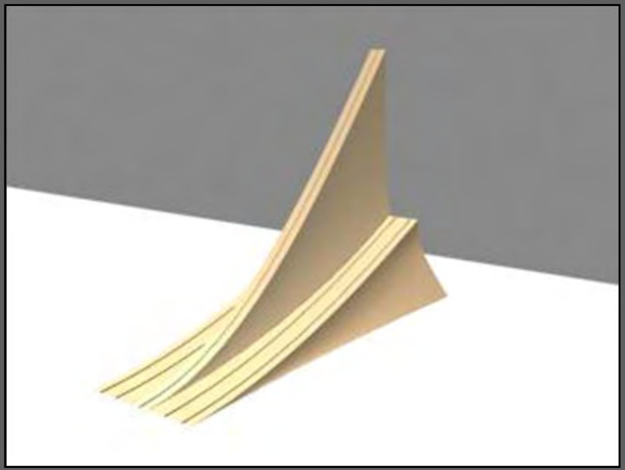
Coil Gun Launch Tube

- High-g launch for water, propellants, and payloads
- Launch assist for conventional rocket systems

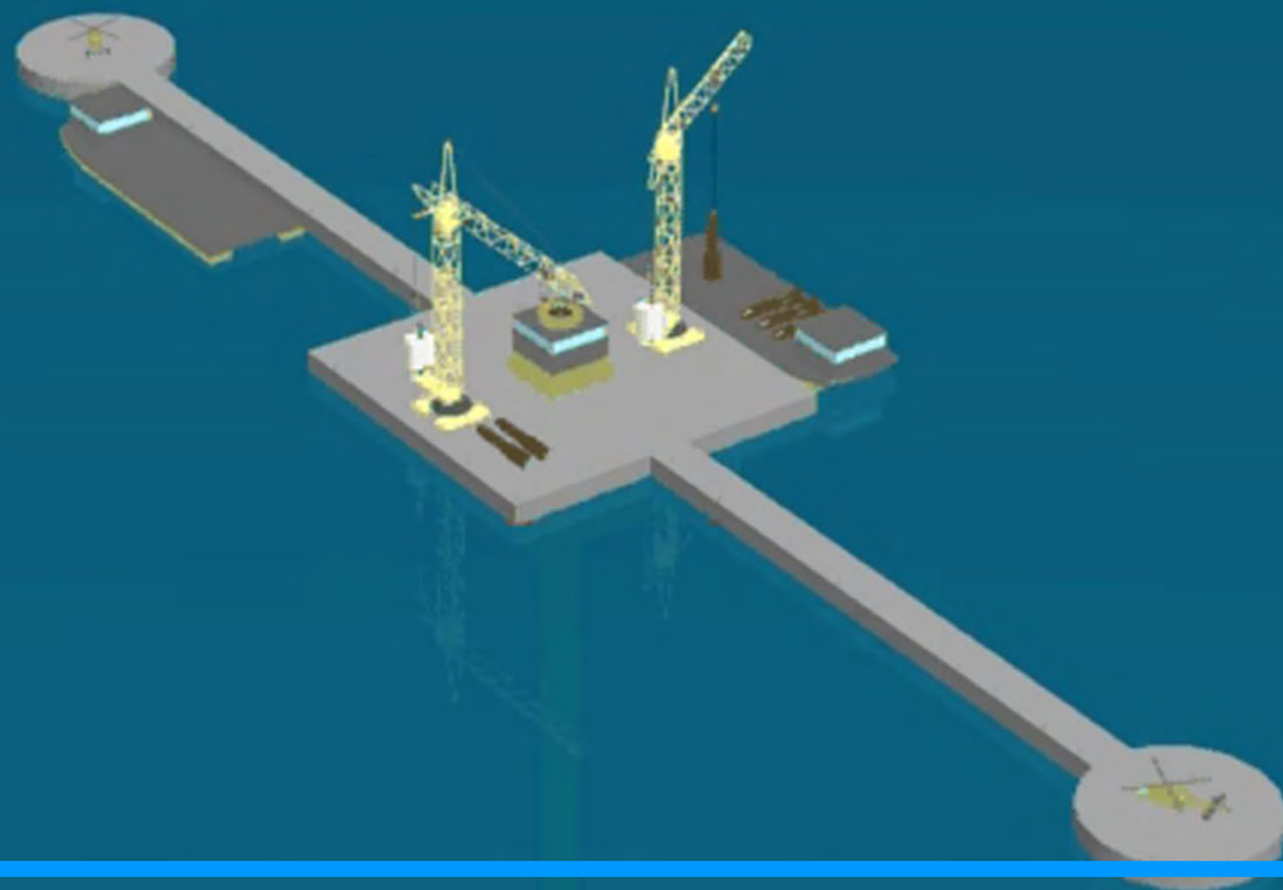
Electromagnetic Launch Rail

- Low-g for passenger transports
- Launch assist for aircraft and future space planes



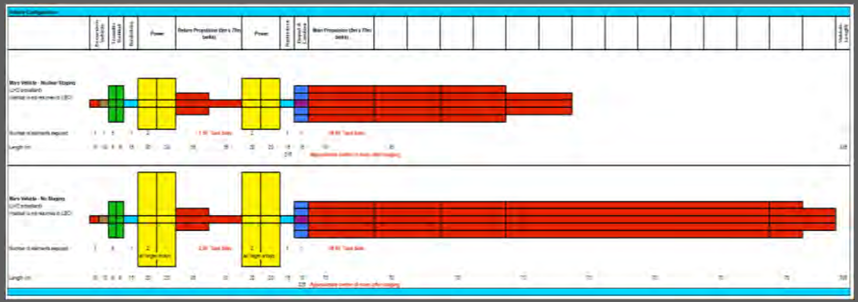


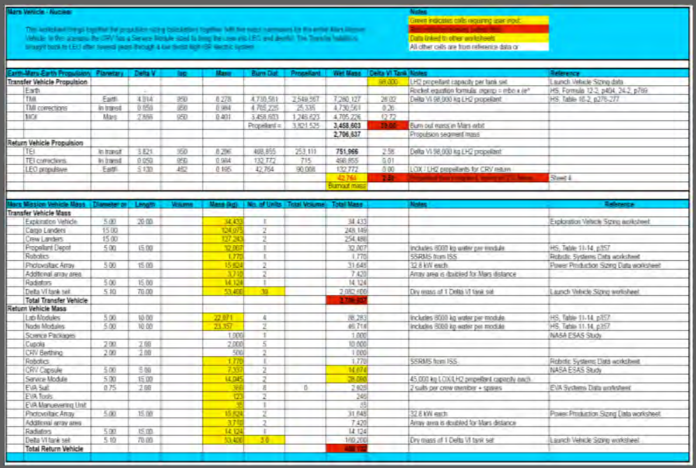
Coil Gun Launch Tube Animation

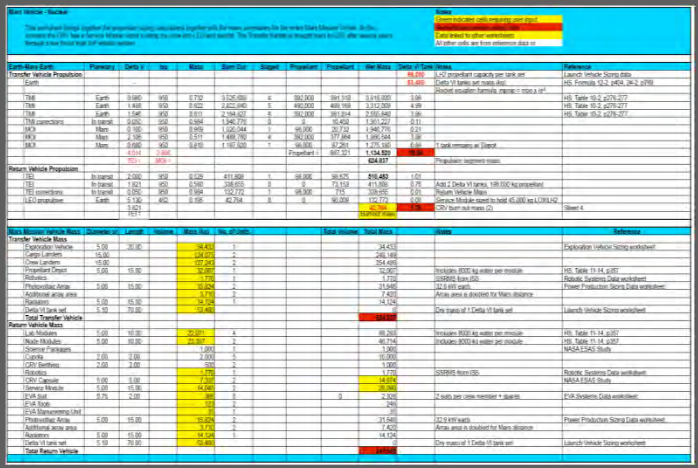


Nuclear Systems

- Findings
  - Nuclear propulsion option was not selected because the large hydrogen tank mass negated the advantages of the high engine efficiency
    - Transfer Vehicle required 39 tanks
    - Staging with drop tanks, 18 tanks required
    - How do you stage a nuclear system with one nuclear engine and drop tanks?





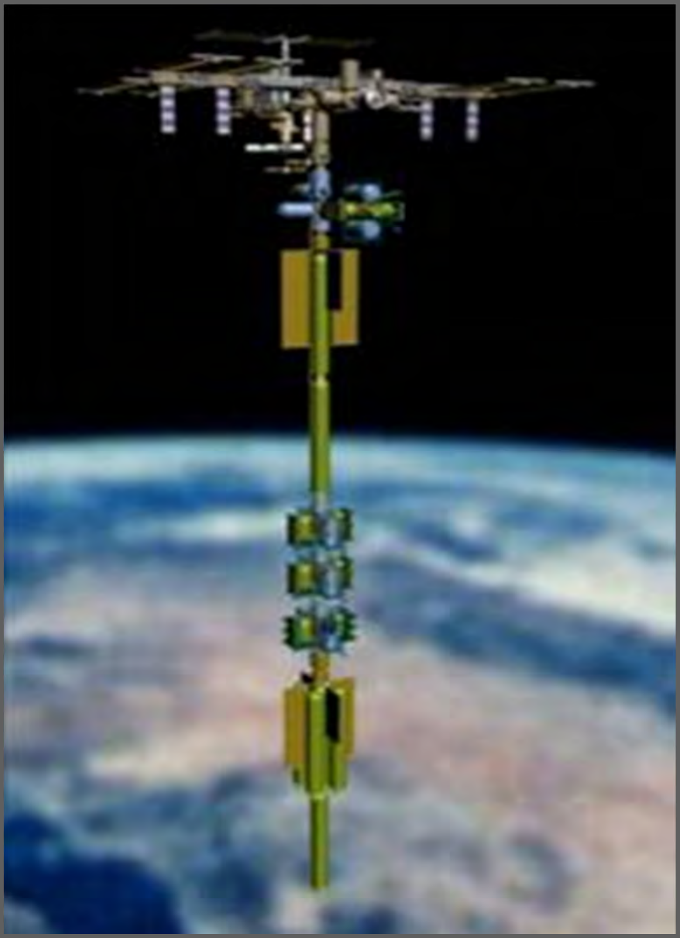


Mars Mission Story Board

Appendix F

Assembly Concept 1

- Assemble entire vehicle from nadir port of ISS
- Issues
  - Requires mobile crane system to travel length of vehicle
  - Requires constant relocation of propulsion system for re-boost



Assembly Concept 2

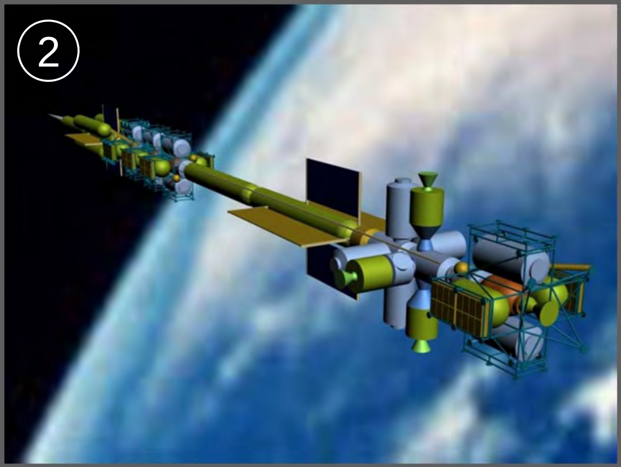
- Assemble habitable sections at ISS and propulsion sections separately
  - Transfer habitats and propulsion module attached to nadir port
  - Landers assembled off transfer habitat ports
  - Propellant depot, power systems and propulsion stages assembled separately

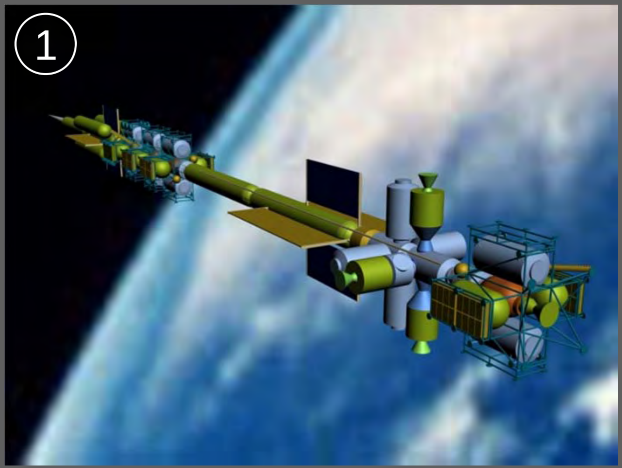
- Benefits
  - Transfer habitats and Landers assembled at the ISS
  - Propulsion elements assembled safely away from ISS
  - Propulsion module or Exploration vehicle used for ISS re-boost

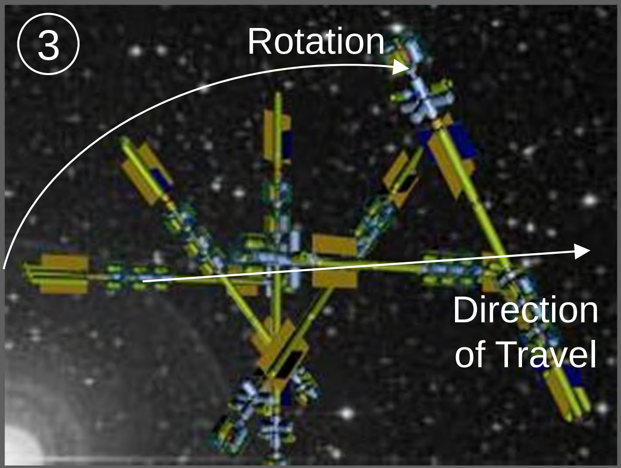
- Issues
  - Options for docking of large masses
    - Automated rendezvous
    - Docking using remote operated mechanical arms
    - Tether connections using winch mechanisms

Earth Departure

1. Earth departure or Trans-Mars Injection (TMI)
2. 1 of 4 TMI stages burn out and drop off.
3. Remaining 3 stages burn out and outer 2 drop off. Center stage remains attached to electrolysis unit (Propellant Depot)
4. Side thrusters rotate habitat

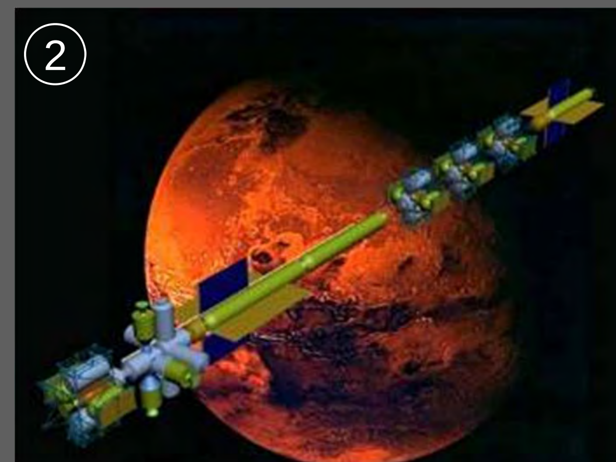


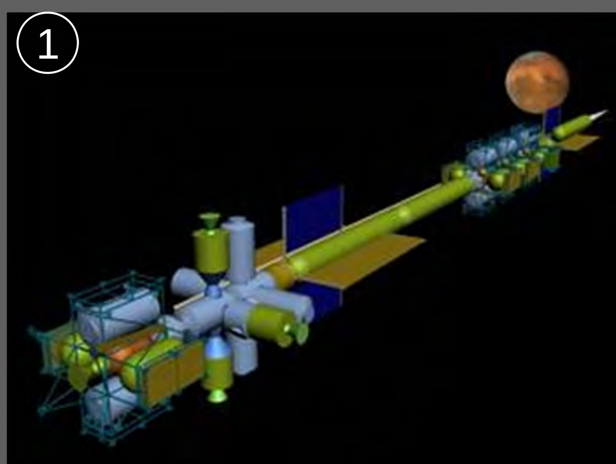




Mars Arrival

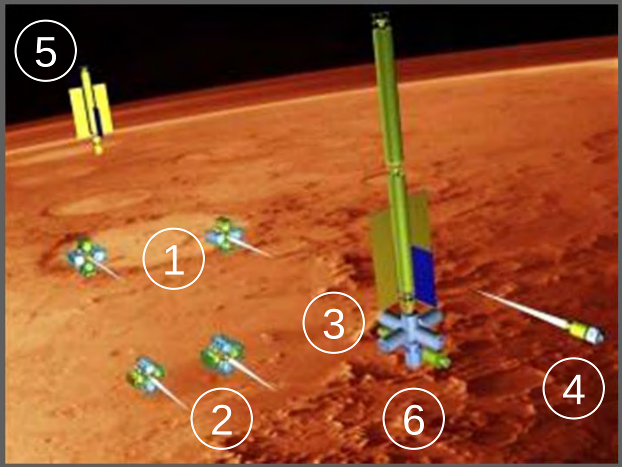
1. Thrusters stop rotation and last two TMI stages are used to de-accelerate and enter into Mars orbit
2. Vehicle separates to reconfigure
3. Remaining TMI stage(s) becomes a free-flying Propellant Depot
4. Landers dock to ports and the ends of the Transfer Habitat modules

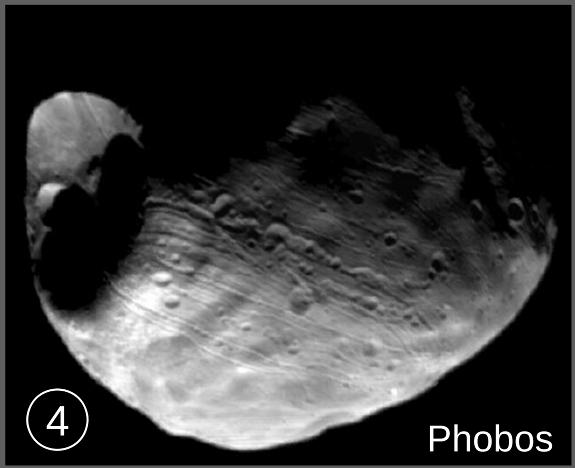




Exploration Scenario

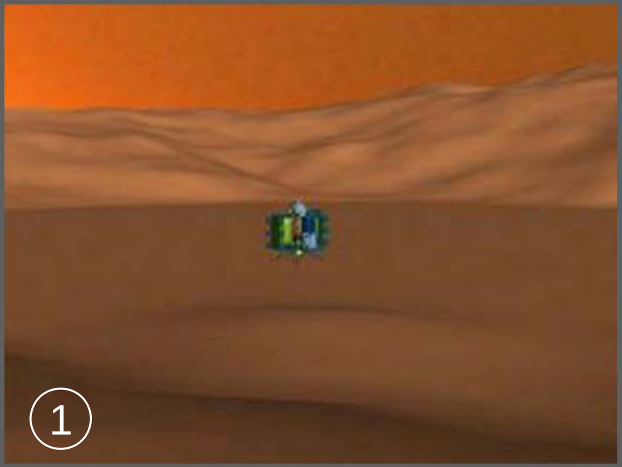
1. Automated Lander 2 and 4 depart first and land near the outpost site. Lander 4 contains power module and pressurized rover
2. 4 crew members depart on Lander 1 to deploy power module and pressurized rover – 4 more depart on Lander 3 once deployment completed
3. An option is for 2 crew members to remain on board the transfer station for the Phobos / Deimos missions
4. The Phobos / Deimos mission is two weeks or longer, so this can be done before during or after the surface stays
5. A surface depot is set up for the two automated Landers to deliver water to the Propellant Depot for propellant production
6. Rotating the Transfer Station at 3 RPM would provide 1/6-g for any long term crew stays while in orbit and during return to earth

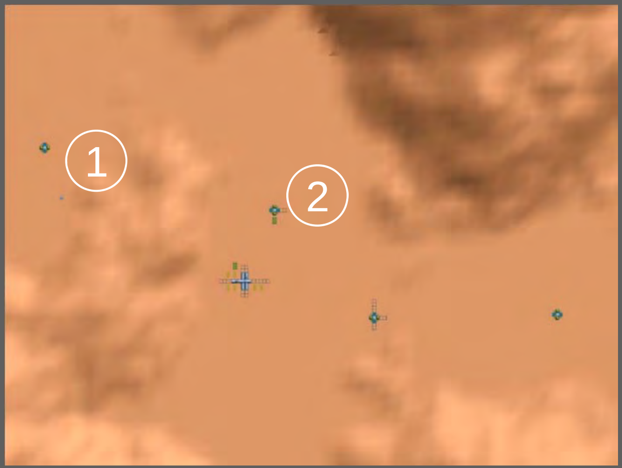




Surface Outpost Setup

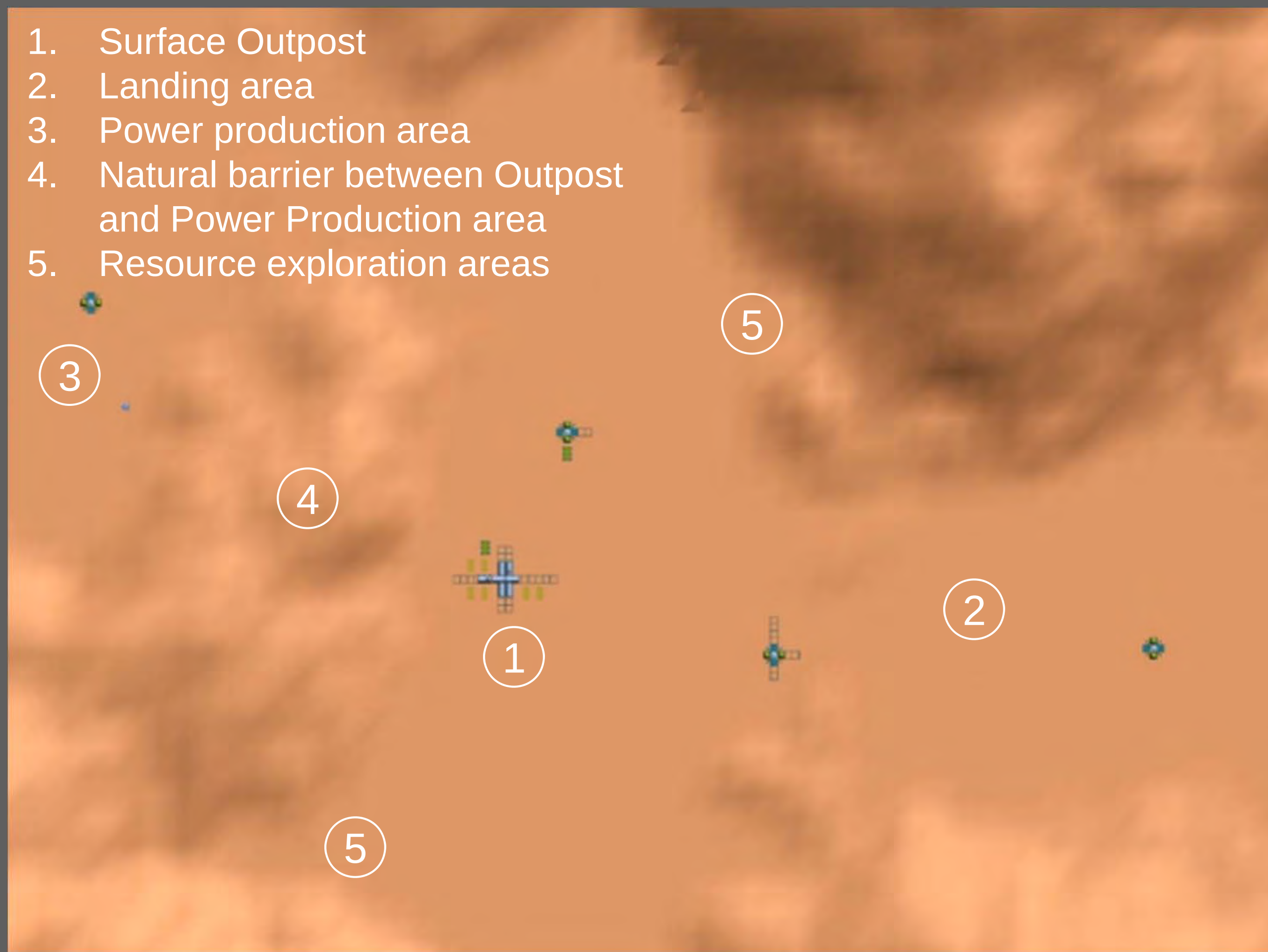
1. Cargo Lander 4 is the first to land in a remote area out of the line of site from the outpost. This will be the location for the nuclear power (NP) unit. Radiation options include:
   - Operate on Lander 4 out of line of site
   - Burial of reactor unit
   - Encapsulation or reactor unit with Martian soil or water obtained from Mars in water bladders
2. Payloads are deployed, and checked out by the Lander 1 crew





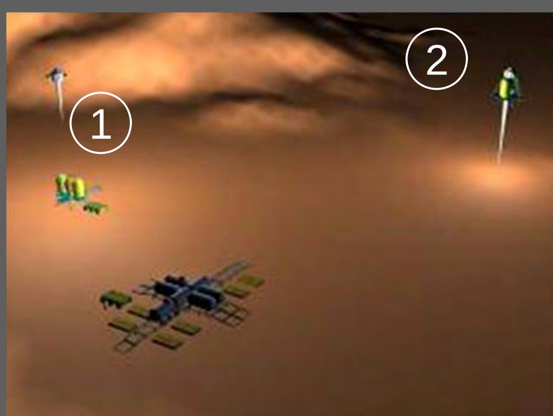
Notional Outpost Site Layout

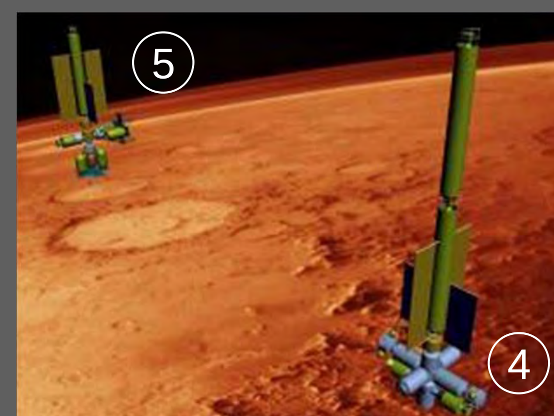
1. Surface Outpost
2. Landing area
3. Power production area
4. Natural barrier between Outpost and Power Production area
5. Resource exploration areas



Mars Departure

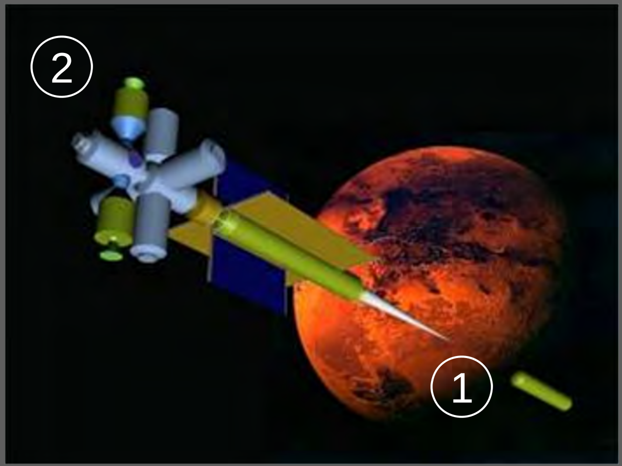
1. Landers 1 and 3 have an Ascent Vehicle on top designed for 4 crew members
2. If surface refueling is successful then the entire Lander can be refueled and used for ascent and descent throughout the mission duration
3. Upon completion of their missions at Phobos and Deimos the other crew members return to the Transfer Station
4. Ascent Vehicles return crew to the Transfer Station
5. Reusable Landers and Transfer Vehicle remain at the Propellant Depot for reuse on future missions

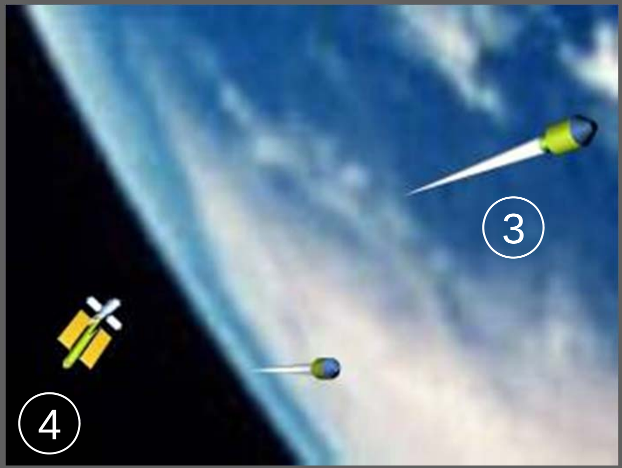




Earth Return

1. Last two stages are used to return the Transfer Habitat to Earth, Trans-Earth Injection (TEI)
2. Habitat can be rotated during the return phase up to 3 rpm for 1/6 g
3. Crew returns directly to surface via the capsules on the 2 Crew Return Vehicles. Each holds 4 crew members plus sample returns
4. Saving the Transfer Station is not possible until after the 3rd mission when an operational propellant production capability is established in Mars orbit and on the surface





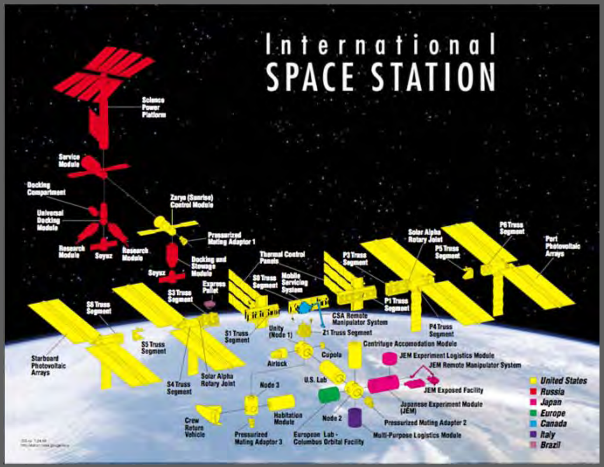
ISS Components Utilized in Design

Appendix G

ISS Statistical Data

- Mass: 232,693 kg (513,000 lb)
- Length:58.2 m (191 ft) along truss
- Width: 44.5 m (146 ft) from Destiny to Zvezda span of solar arrays
- Height:27.4 m (90 ft)
- Living volume 424.75 m³ (15,000 ft³)
- Atmospheric pressure: 101.3 kPa (29.91 inHg)

- Perigee: 339.3 km (183.2 nmi)
- Apogee: 341.8 km (184.6 nmi)
- Orbit inclination: 51.64 degrees
- Typical orbit altitude: 340.5 km (183.86 nmi)
- Average speed: 27,743.8 km/h (17,239.2 mi/h, 7706.6 m/s)
- Orbital period: 91.34 minutes
- Orbits per day: 15.76



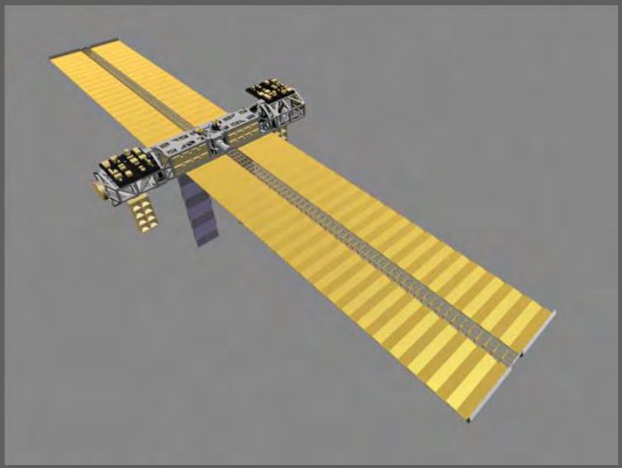
ISS Derived Power & Thermal

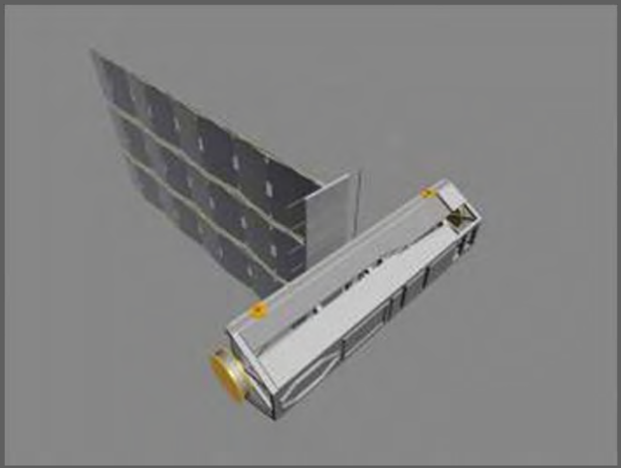
28 kW Solar Power Unit

- Standard unit provides power for habitat and propellant depot systems
- Derived from ISS systems
- Includes storage batteries
- Design provides for rotational mechanisms to track sun

Thermal Radiator Unit

- Derived from ISS systems
- Thermal radiators include a fluid loop from the habitat to provide transfer of waste heat out of the habitat





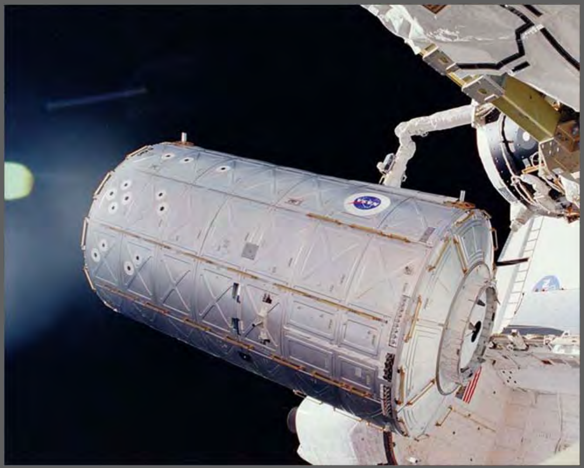
Space & Surface Habitat Modules

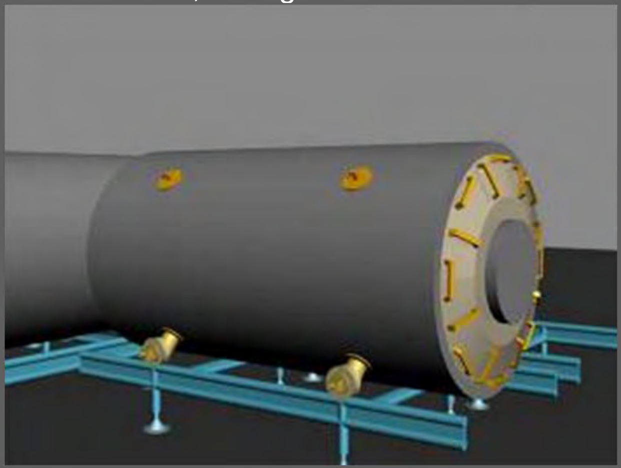
ISS Destiny US Laboratory Module

- Specifications
  - Length: 8.53 m
  - Diameter: 4.27 m
  - Mass: 14,500 kg (32,000 lb)

Laboratory Module

- 4 Laboratory modules include
  - Materials
  - Mission Operations
  - Life Sciences
  - Greenhouse
- Specifications
  - Length: 10 m
  - Diameter: 5 m
  - Mass: 18,918 kg





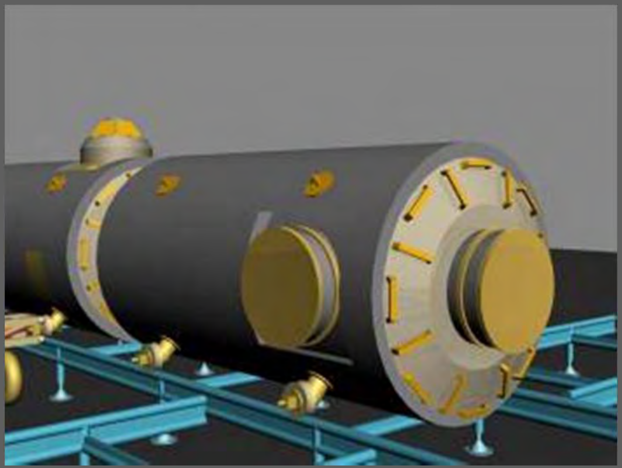
Space & Surface Habitat Modules

ISS Harmony Node II

- Specifications
  - Length: 7.2 meters
  - Diameter: 4.4 meters
  - Volume: 75 cubic meters
  - Mass: 14,288 kilograms

Node Module

- 2 Node modules include a built-in airlock
  - EVA Node / Airlock
  - Galley Node / Airlock
- Specifications
  - Length: 10 m
  - Diameter: 5 m
  - Mass: 21,369 kg



Other Attached ISS Components

ISS Cupola

- Specifications
  - Overall height: 1.5 m
  - Maximum diameter: 2.95 m
  - Mass: 1,880 kg

ISS Quest Airlock

- Specifications
  - Material: aluminum
  - Length: 5.5 m (18 ft)
  - Diameter: 4 m (13 ft)
  - Weight: 6,064 kg (13,368 lb)
  - Volume: 34 m^3 (1,200 ft^3)
  - Cost: $164 million, including tanks
- Capabilities included in Node modules

ISS Robotic Systems

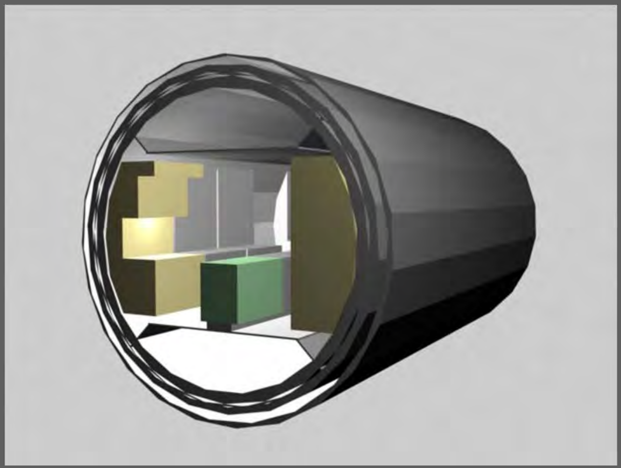
- All ISS robotic systems are used as a baseline for the assembly and maintenance systems for the Lunar Test Mission Vehicle and the Mars Ship

Payload Racks

ISS International Standard Payload Rack (ISPR)

- Specifications
  - Slots available: 64
  - Volume: 1.571 m^3 (5.55 ft^3)
  - Rack Mass: 104 kg (230 lbs)
  - Equipment Mass: 700 kg (1540 lbs)
  - Sub-rack accommodations:
    - Spacelab drawers: 483 mm (19 in) width
    - Space Shuttle Mid-deck Locker

- Standard Payload Racks utilized in walls
- Air & power systems above Ceiling
- Water and storage systems below floor
- 7 foot floor to ceiling height
- 8 foot width to accommodate center counter



ISS Multi-Purpose Logistics Module

- Modules like the Multi-Purpose Logistics Module (MPLM) are anticipated for all recurring missions at the Moon and Mars. The open end ports on all surface habitat modules are designed for mating of additional modules

MS-SPACE ARCHITECTURE

SICSA

Sasakawa International Center for Space Architecture
Gerald D. Hines College of Architecture, Univ. of Houston

. . . and on to the Stars!