Critical Design Review

Space Station Phoenix

ENAE 484: Space Systems Design

The Future of NASA

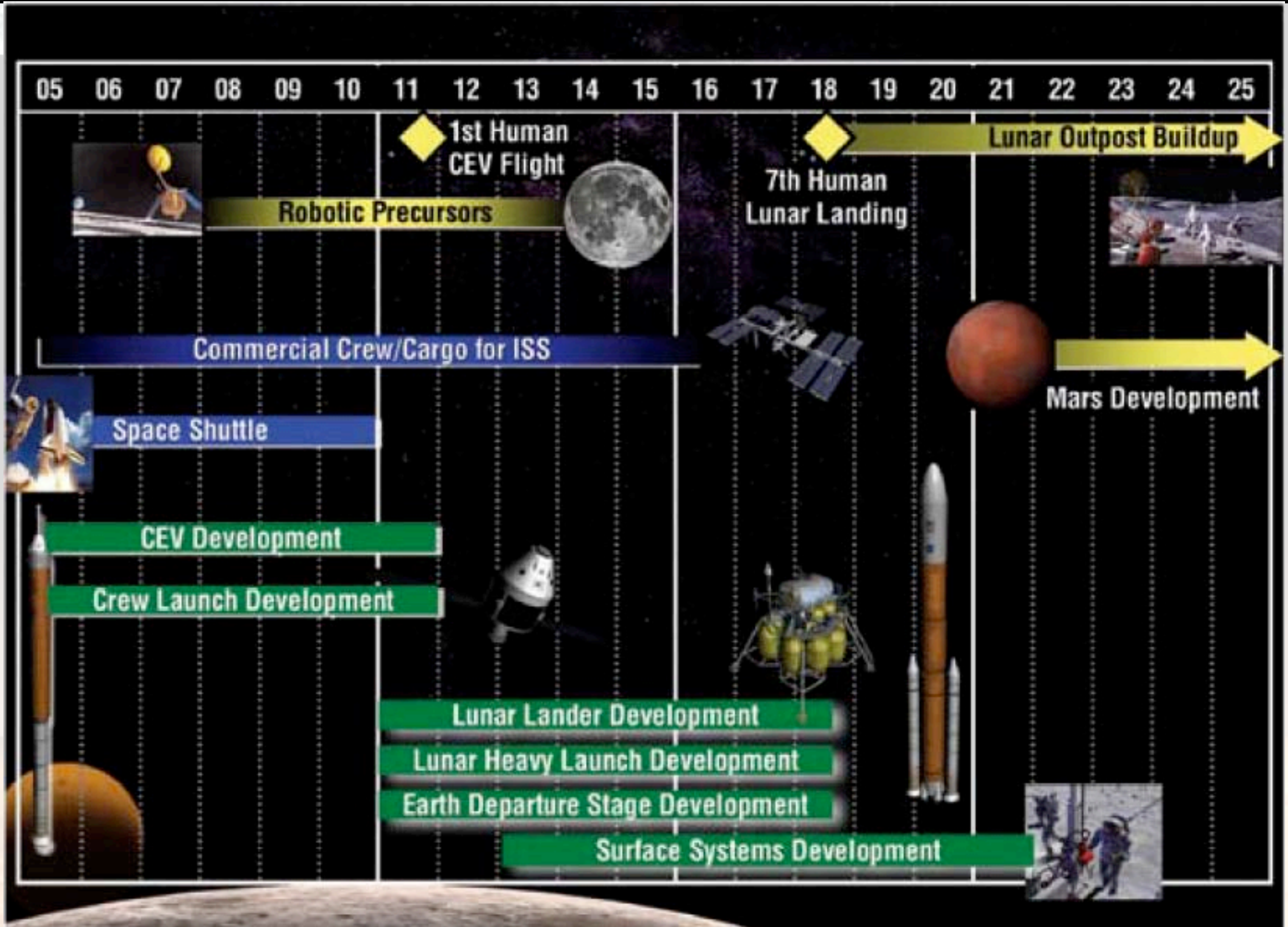


Image: http://images.spaceref.com/news/2005/ESAS.REPORT.14.PDF

What Do We Need to Get to Mars?

There are still many unknowns surrounding a Mars mission:

- How will humans respond to prolonged fractional gravity?
- How will the astronauts acclimate to Mars gravity?
- What EVA operations will be performed on Mars?
- What tools will be needed to conduct EVAs?
- What will it take to sustain humans on Mars?

The Cost of the Data

- Current estimates place a Mars simulation station at costs near those of a manned mission to Mars itself
- After International Space Stations (ISS) disassembly in 2016, majority of NASA's budget is concentrated on the 7th lunar landing
- NASA has invested $100B in ISS; current architecture misses opportunity to exploit this resource

Space Station Phoneix (SSP)

- Starting in 2017, SSP accomplishes NASA's goals for Mars research and development by 2027
- Through a renovation of ISS, SSP answers critical questions about manned Mars missions for less than $20B
- No other solutions currently exist to simulate Mars environment

Space Station Phoenix Goals

Decommission the International Space Station

↓

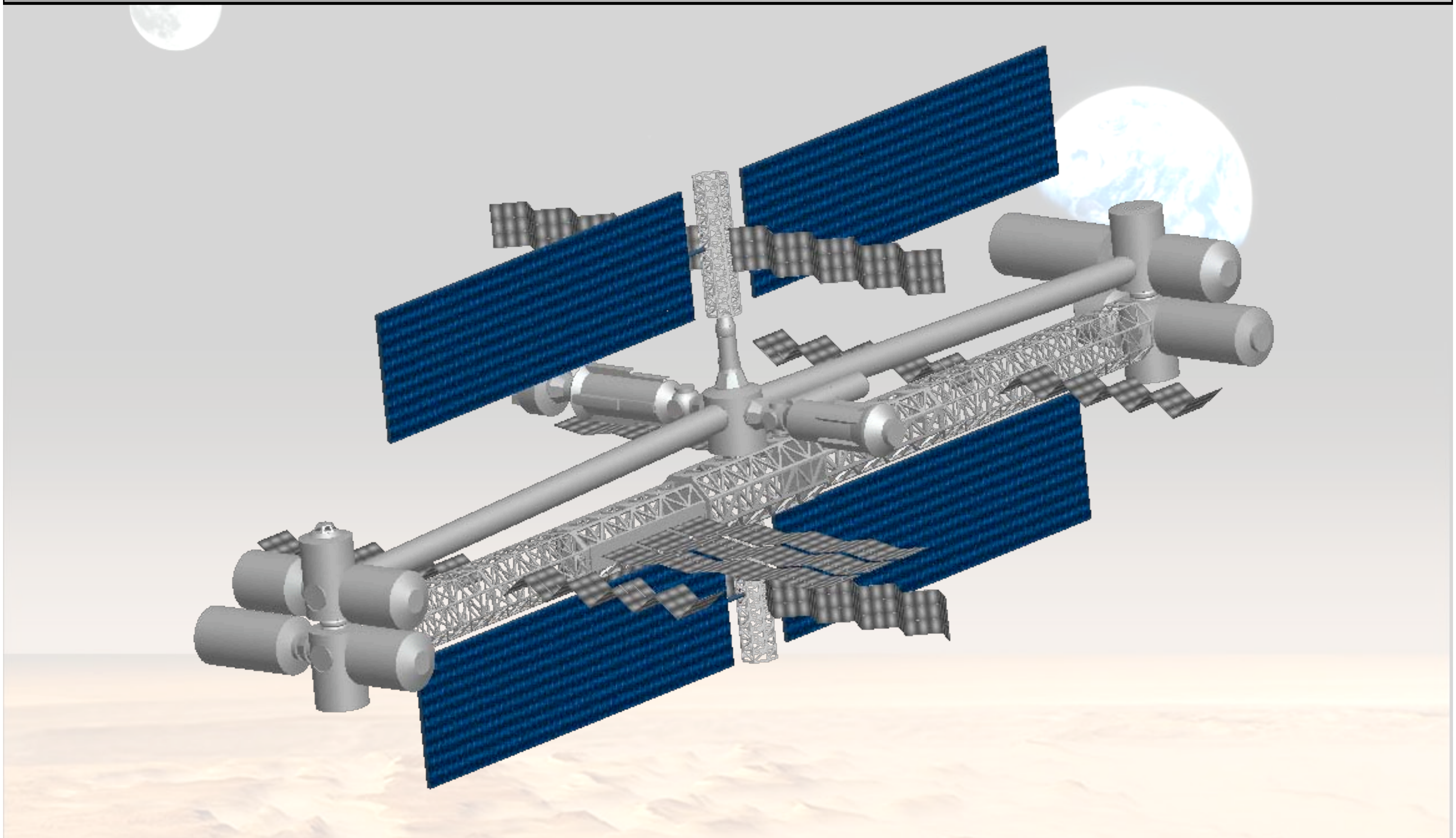
Reuse as many existing components as possible

↓

Construct a “Space laboratory” – (SSP)

Learn how to keep humans alive in space for trips to and from Mars and during extended stays on both Mars and the Moon

Solution: Space Station Phoenix



Space Station Phoenix

- ISS-derived design, comprise mainly of reused ISS components
- Remains in ISS Low Earth Orbit (LEO)
- Can produce between 0 and 1g artificial gravity
- Can support six people for up to three years without re-supply

General Requirements

- SSP shall be capable of a 3-year simulation of a Mars mission without re-supply, including EVA and emergency operations. [#1]
- SSP shall be used to study the effect of variable gravity on human physiology from 0 to 9.8 m/s^2. [#5, #8]
- SSP interior pressure shall operate between 8.3 and 14.7 psi [#20]

General Requirements (cont.)

- SSP shall have a crew of 6 and shall accommodate crew between 5th percentile Japanese female and 95th percentile American male. [#7, #21]
- SSP shall provide a radiation environment not to exceed NASA standards for exposure. [#19]

ISS Related Requirements

- SSP shall use components from ISS and other NASA programs as much as possible. [#14, #27]
- SSP shall provide all communications currently provided by ISS with the addition of two full-time HDTV downlinks. [#17]
- All crew interfaces shall adhere to NASA-STD-3000, Man-System Integration Standards. [#22]

Safety Requirements

- Evacuation to Earth shall be available at all times. Alternative access and EVA "bailout" shall be provided. [#2, #23]
- All safety-critical systems shall be two-fault tolerant. [#18]
- All structural systems shall provide non-negative margins of safety for all loading conditions in all mission phases. [#26]

Safety Requirements (cont.)

- SSP shall follow NASA JSC-28354, Human Rating Requirements. [#16]

- Structural design factors shall use NASA-STD-5001, Design and Test Factors of Safety for Spaceflight Hardware. [#24]

- Analyses shall use NASA-STD-5002, Load Analysis of Spacecraft Payloads. [#25]

Timeline Requirements

- SSP construction shall begin Jan. 1, 2017. [#3]
- SSP shall simulate a full-duration Mars mission by Jan. 1, 2027. [#4]
- SSP will use American launch vehicles that exist in 2016, and will provide standard interfaces to them. [#6, #10]
- SSP shall only use technology currently at or above Technology Readiness Level (TRL) 3 and at TRL 6 by 2012. [#11]

Cost Requirements

- Total SSP costs shall be less than $20B (in 2006 $). [#13]
- SSP nominal operating costs, including launch and in-space transportation, shall be no more than $1B (in 2006 $) per year after construction. [#12]
- Cost estimation shall use NASA standard costing algorithms. [#15]

Orbit Location

Will stay at the orbit of ISS

- Apogee: 349 km altitude
- Perigee: 337 km altitude
- Eccentricity: 0.0009343
- Inclination: 51.64°
- Argument of Perigee: 123.2°
- Period: 92 minutes

Choosing a Rotation Rate

- *Lackner* study demonstrated that 10 rpm can be tolerable if spatial disorientation is mitigated with head movements during acceleration
- Discomfort due to vestibular and ocular sense of Coriolis acceleration forces

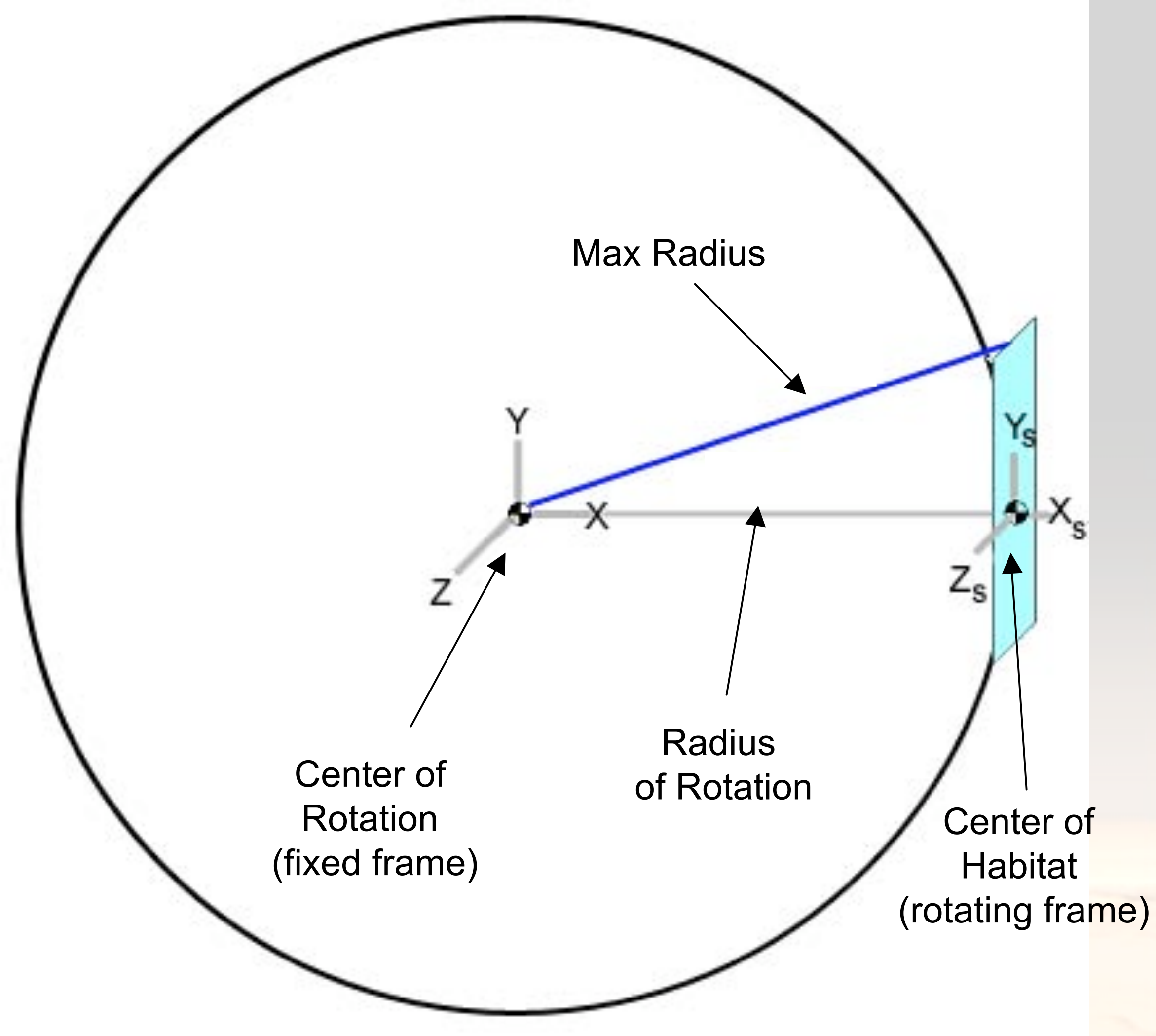
Comfortable Rotation Rates in Artificial Gravity

Author/ Study	**Year**	**Minimum Apparent G's**	**ω** (rpm)
Hill & Schnitzer	1962	0.04	4
Gilruth	1969	0.30	6
Cramer	1985	0.10	3
Lackner	2003	0.10	10

4.5 rpm chosen to strike a balance between minimizing the Coriolis force disturbance to the crew and minimizing the size of the rotating arms

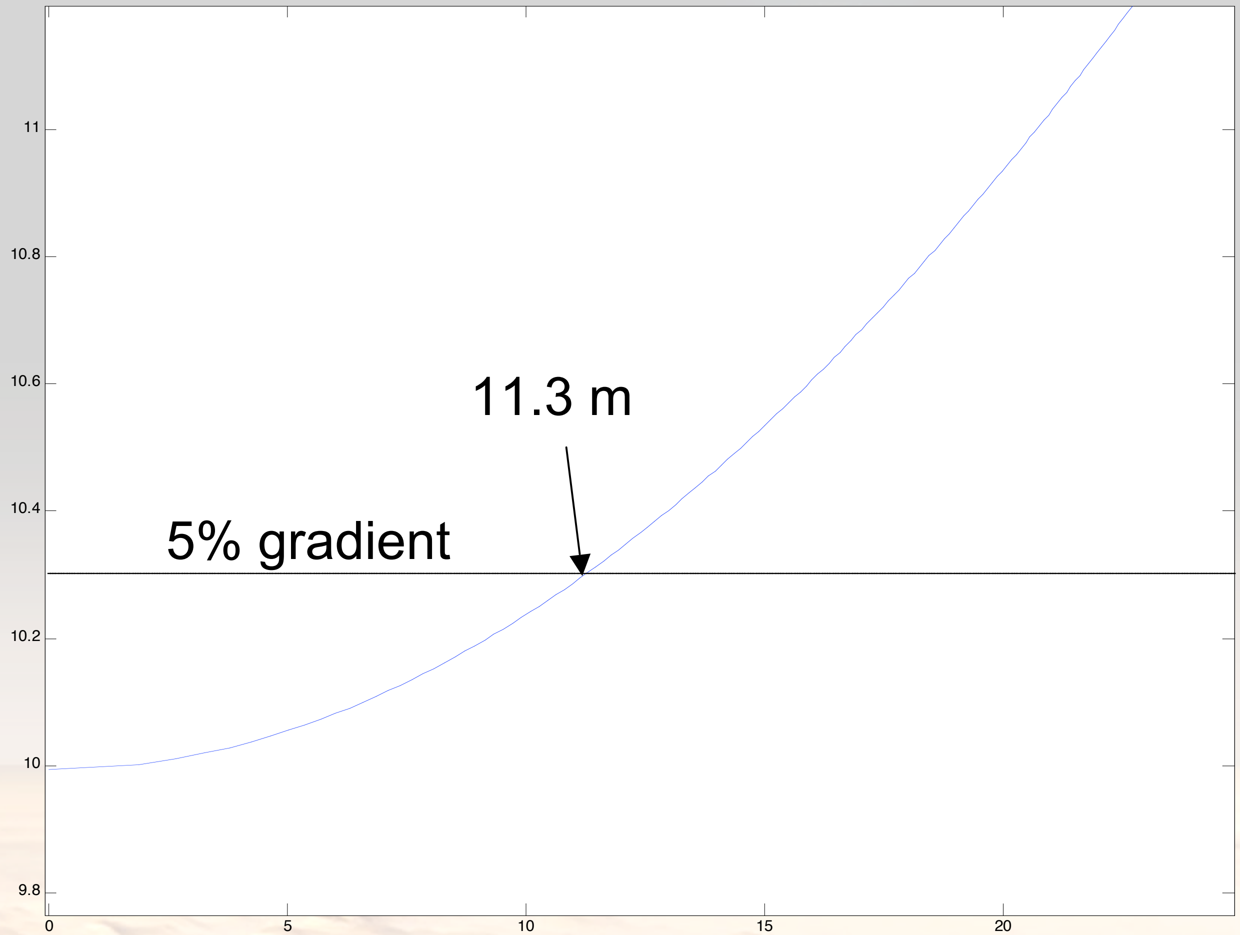
Rotational Orientation

- Station is rotating about the frame's Z axis. Anything along the Z_s axis will experience the desired gravity
- Building along the Y_s axis will increase the value of the radius of rotation, and thus the gravity from the center to the end of the station will be increasing
- Gravity conditions will also increase when building along the X_s+ (Building along X_s- will cause a decrease)



Limits of Construction

- Level 1 requirements mandate that the station produce variable gravity conditions
- ±5% gravity "window" determined to be acceptable
- Max allowable construction envelope is 11.3 m along the station's ±Y axis

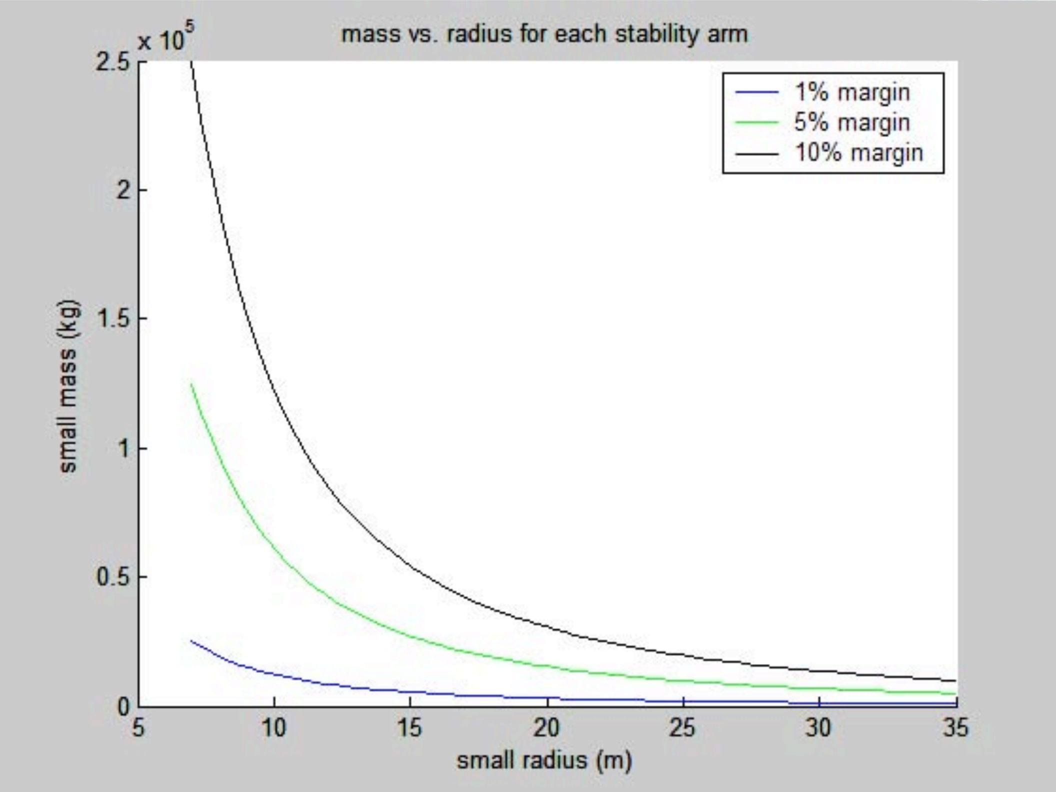


Configuration Stability

- If the three principal moments of inertia are different, rotation about the largest and smallest are stable to small perturbations, rotation about the middle is unstable
- Compared stability arm mass at various radii to determine differences between the largest and middle principal moments of inertia for a dumbbell with stability arms

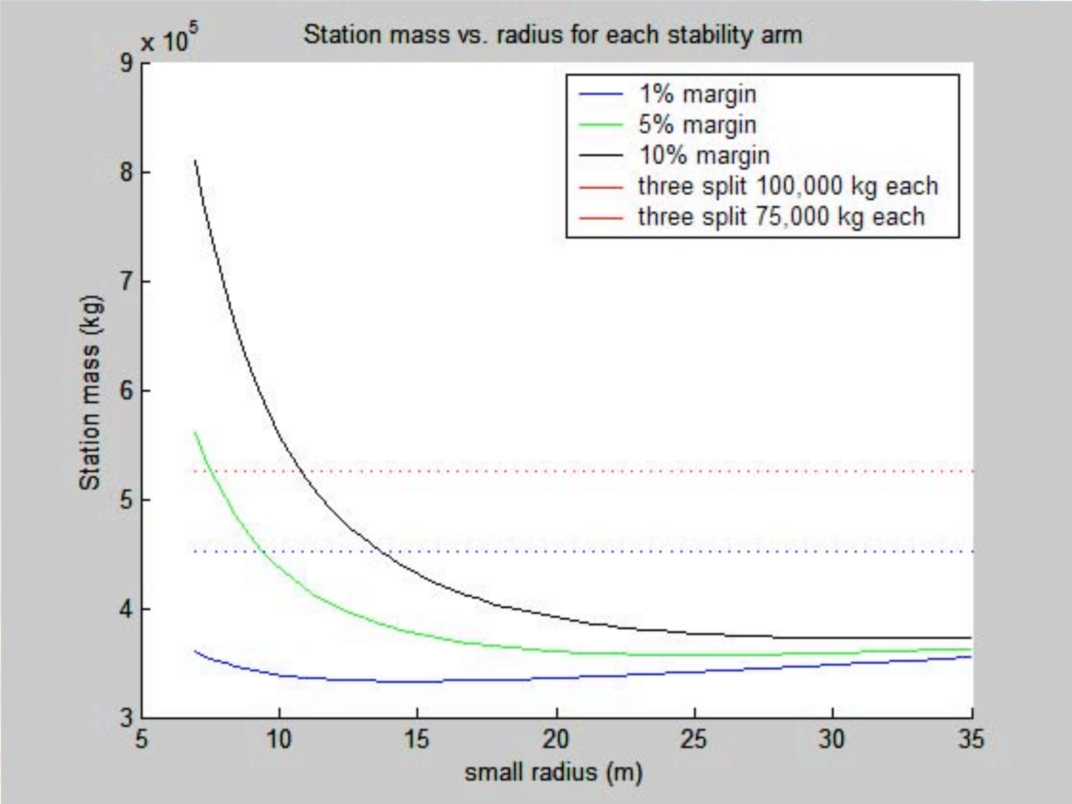
Dumbbell Approach

Differences of 1%,5%,10% for stability margin of dumbbell approach



Dumbbell vs. Three Spoke

Added in mass of trusses and central axis to compare with the mass of a three spoke design



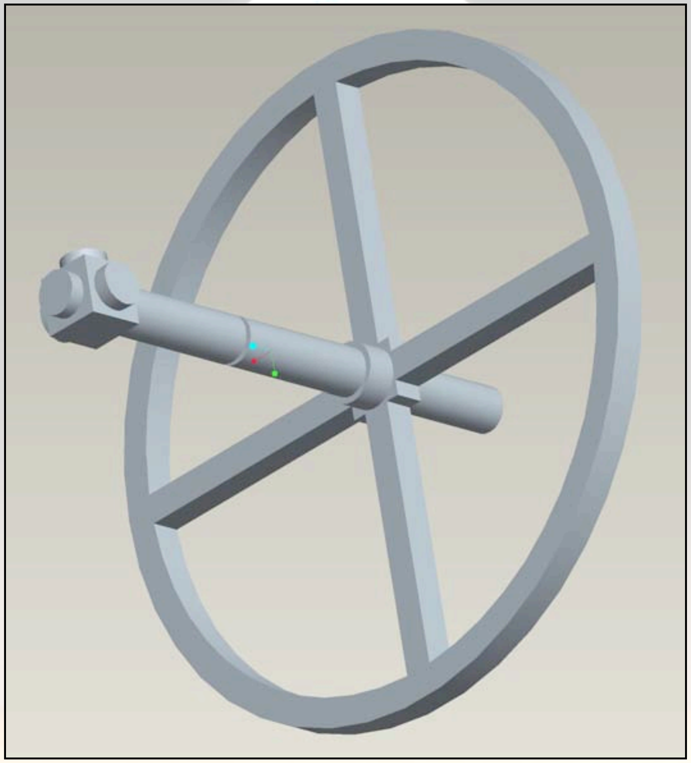
Decision

Dumbbell approach with stability arms was chosen over other designs:

- Less mass
- Fewer new parts to produce
- Less propellant for maneuvering
- Lower cost

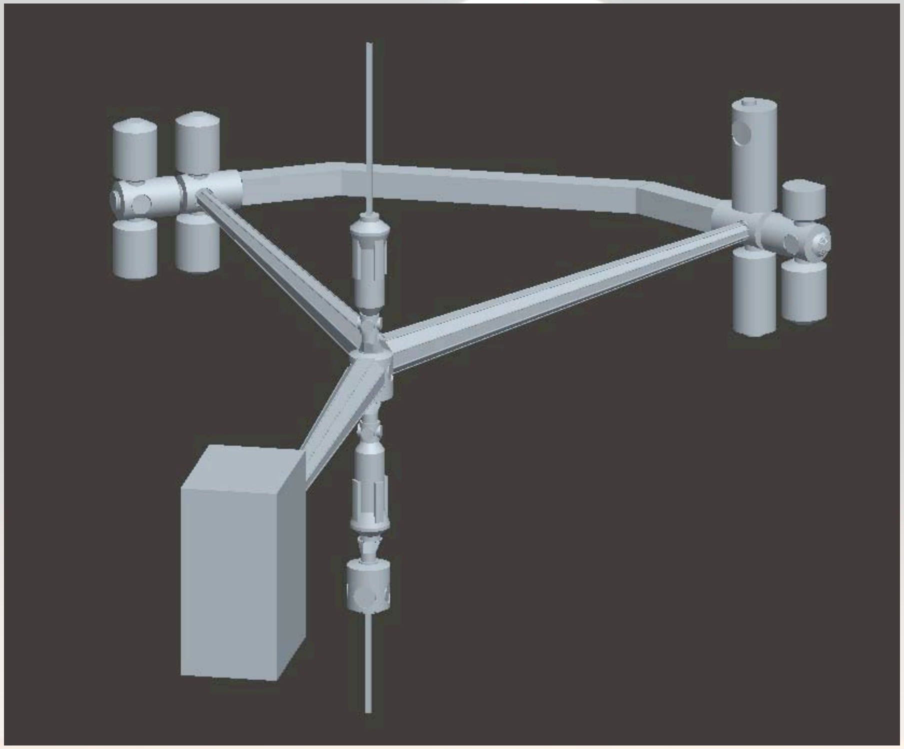
PDR Option 1: Full Wheel

- More crew space than necessary
- Two additional trusses to be built and launched
- Several new modules needed to meet configuration
- Unnecessarily large volume of inflatables to complete wheel



PDR Configuration

- Not splitting the crew → large counter mass, increased price/mass of station
- Three-spoke approach, two "townhouses" 60º apart, inflatable connection tubes
- Station mass of over 1,000,000 kg and billions over budget



New Configuration

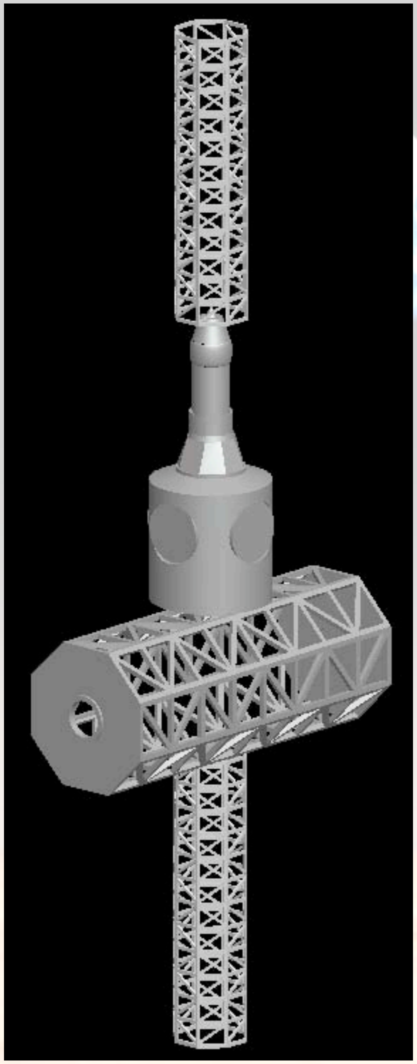
- Crew can be split if they spend less than 5% of their time in transfer between townhouses
- Keeping SSP in LEO
  - No need for heavy radiation shielding
  - No need for orbit transfer propellant

Non-rotating Section

- Solar panels
  - Maintain orientation to the sun
  - Maximize power output by incident angle
- Docking module
  - Allows for docking during simulated Mars mission
  - Limits risk of collision with approaching spacecraft
  - Simplifies docking procedure as much as possible
- Orbit maintenance and attitude control
  - High precision maneuvers
  - Maximize effectiveness of thrusters
- Create central axis to accomplish these goals

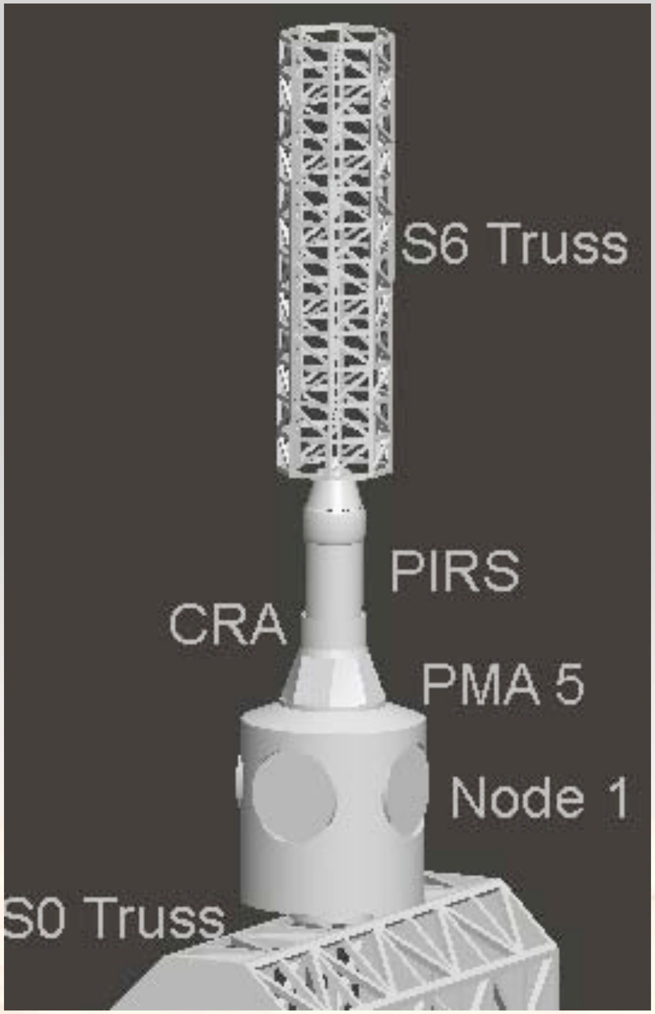
Central Axis

- Non-rotating section
- Docking
- Orbit maintenance
- Attitude control
- Solar panels



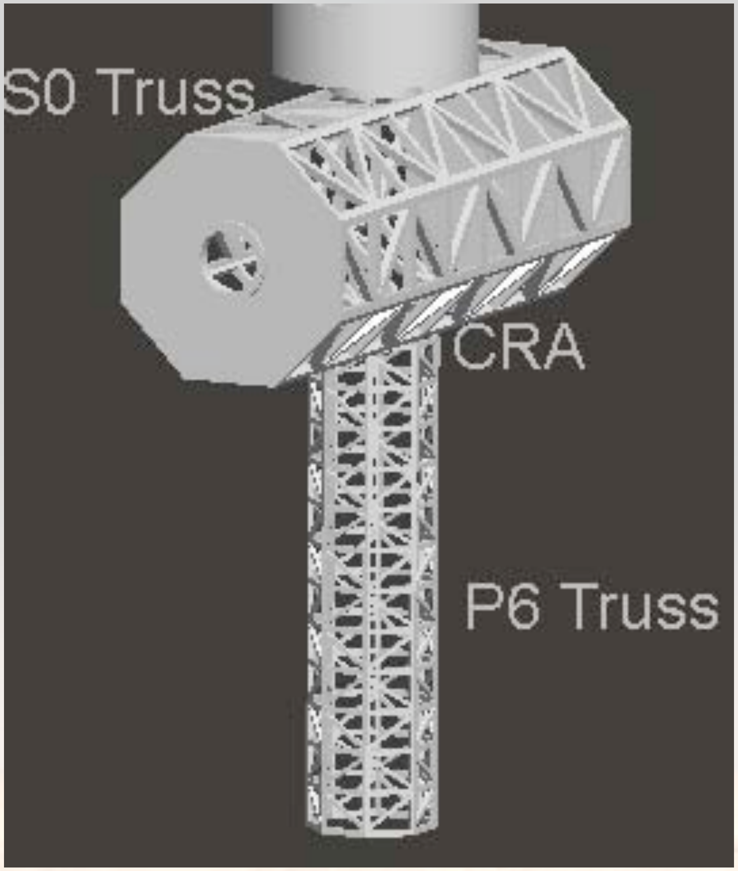
Central Axis (Top)

- Node 1
  - Central hub of the station
  - Mounted on top of S0 truss
- Pressurized Mating Adapter (PMA) 5
  - Provides interface between Russian and US modules
- Counter Rotating Assembly (CRA)
  - Negates effect of rotating station
- PIRS
  - Provides two docking ports for CEV
  - Retrofitted on ground with two CEV adapters
  - Convert airlock hatches to docking ports
- S6 truss
  - Locates propulsion package away from station
  - Provides non-rotating platform for solar panels
- Propulsion package
  - Thrusters and propellant tanks
  - Attached to end of S6 truss



Central Axis (Bottom)

- Counter Rotating Assembly (CRA)
  - Negates effect of rotating station
- P6 truss
  - Locates propulsion package away from station
  - Provides non-rotating platform for solar panels
- Propulsion package
  - Thrusters and propellant tanks
  - Placed at end of P6 truss



Counter Rotating Assembly

- Bearing
  - Allows central axis to remain stationary
  - Handles loading of spacecraft docking
  - Externally geared turntable bearing
  - Commercial designs need to be space-rated
- Drive motor
  - Stepper-motor provides accurate rotation
  - Gear motor to operate at moderate rpms
  - Smooths out traditional pulses of motor
  - Space-rated motors are available
- Seal
  - Rotating air union joint
  - Maintain station environment
  - Commercial designs need to be space-rated

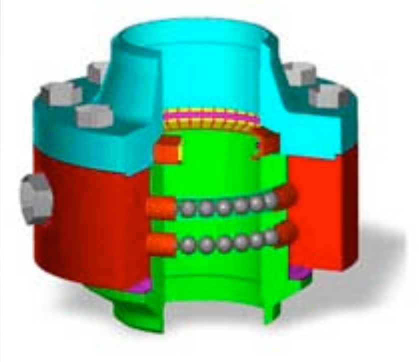
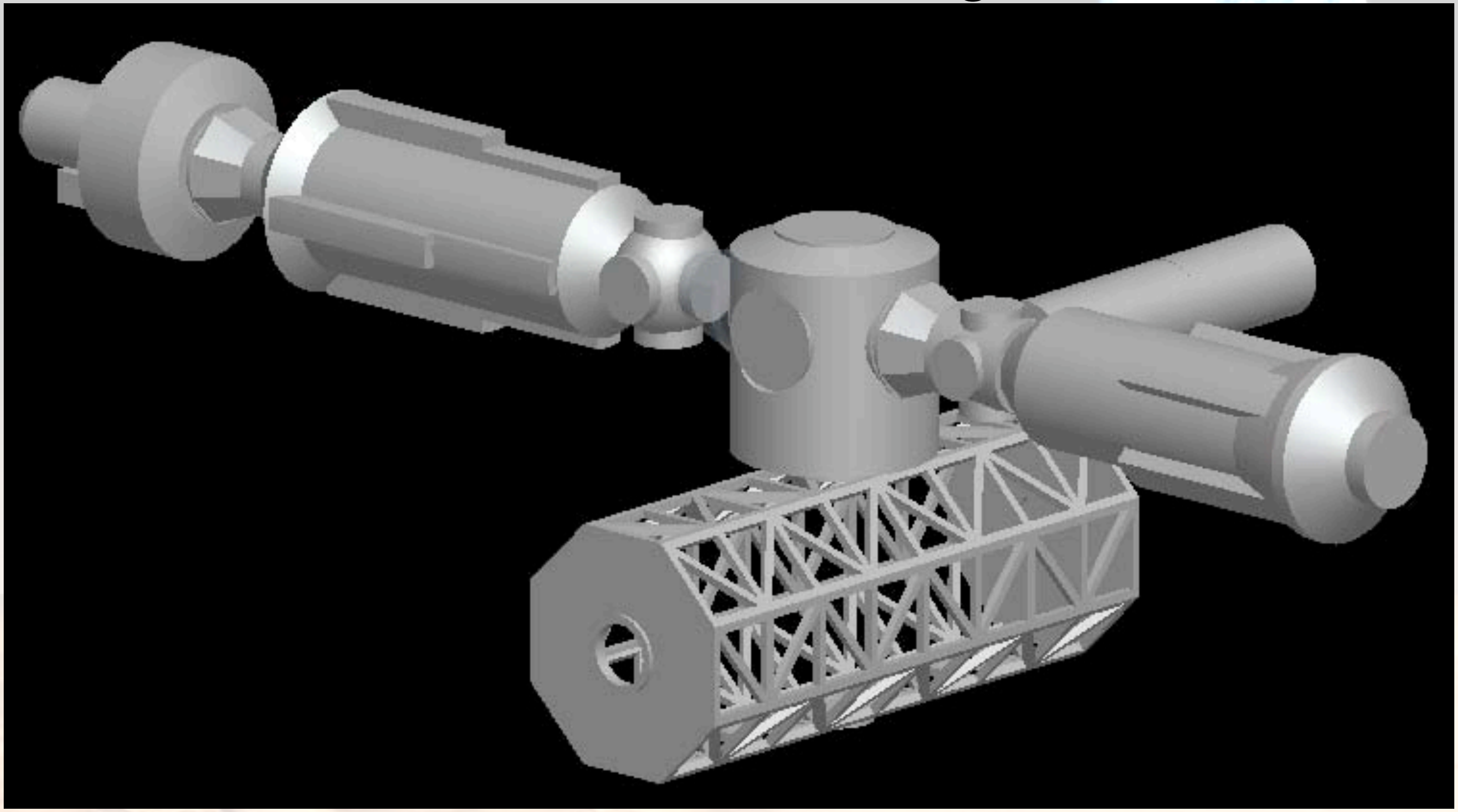


Image: http://www.fmctechnologies.com

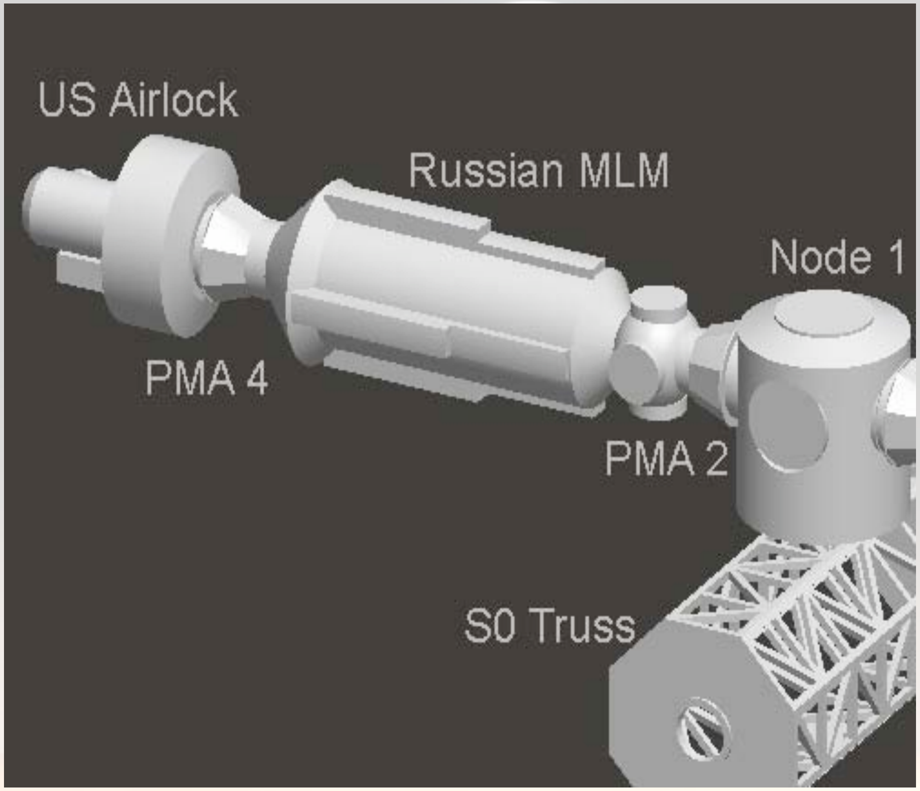
Stability Arm

- Stabilizer bar similar to helicopter rotor designs
- Added to stabilize station during rotation



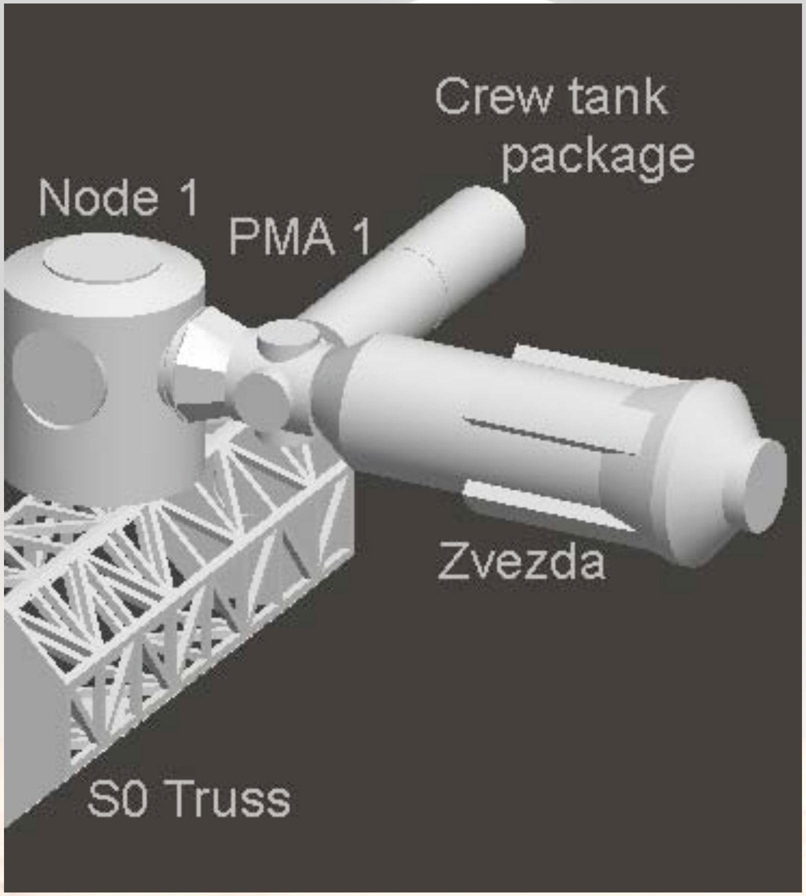
Stability Arm (Left)

- PMA 2
- Russian Multipurpose Laboratory Module (MLM)
  - Experiment and cargo space
  - Backup attitude control system
  - Alternative docking ports (Russian)
- PMA 4
- U.S. Airlock
  - Provide airlock for EVA operations
  - Storage of U.S. space suits and EVA equipment



Stability Arm (Right)

- PMA 1
- Crew tank package
  - Storage of liquid hydrazine and water
  - Attached to docking port of Zvezda
- Zvezda
  - Flight control system
  - Data processing center
  - Supports current automated supply vehicles
  - Alternative docking options (Russian)



Stability Arm Analysis

- Bending assumed negligible
  - Soft docking from CEV
  - Attitude control outputs maximum 12 N per thruster
- Axial loading is driving force
  - Radial acceleration increases linearly
  - Assume uniform mass distribution for modules
  - Integrate to find total force for each arm
- With peak radial acceleration less than 5 m/s^2, each arm must resist approximately 80 kN

Stability Arm Support Structure

- Rods form box around Node 1 to transfer loading to S0 truss
- Four rods extend along the modules
- Rods clamp to trunnion points on modules to transfer axial loading, and frame the structure to resist minor bending
- Central frame members
  - Diameter: 0.02 m
  - Total mass: 53 kg
- Extending rods
  - Total cross section area: 5.5×10^{-4} m^2
  - Total mass: 47 kg

Total Mass

- **100 kg**

Al 6061
Tensile strength 290 MPa
Density 2700 kg/m^3

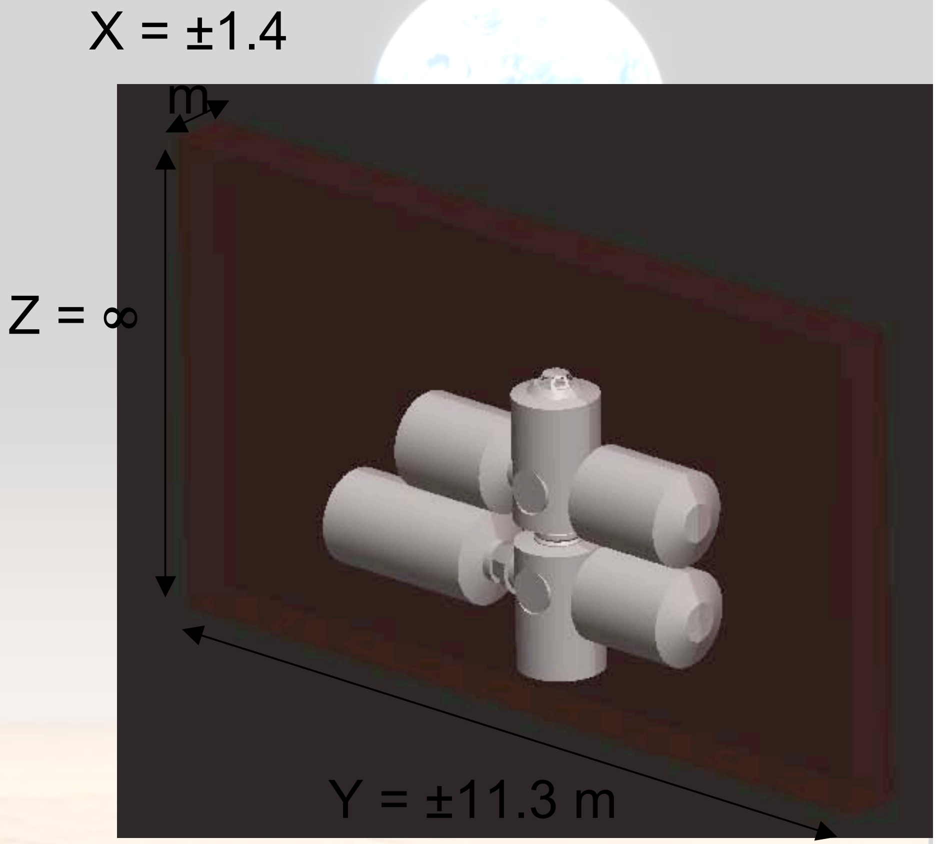
Connections

- ISS uses Common Berthing Mechanism (CBM) to connect modules
- Passive ring attaches to one berthing point
- Active ring attaches to berthing point on corresponding module/node
- Latches pull passive and active rings together
- Bolt actuators load 16 bolts up to 8,750 kg each

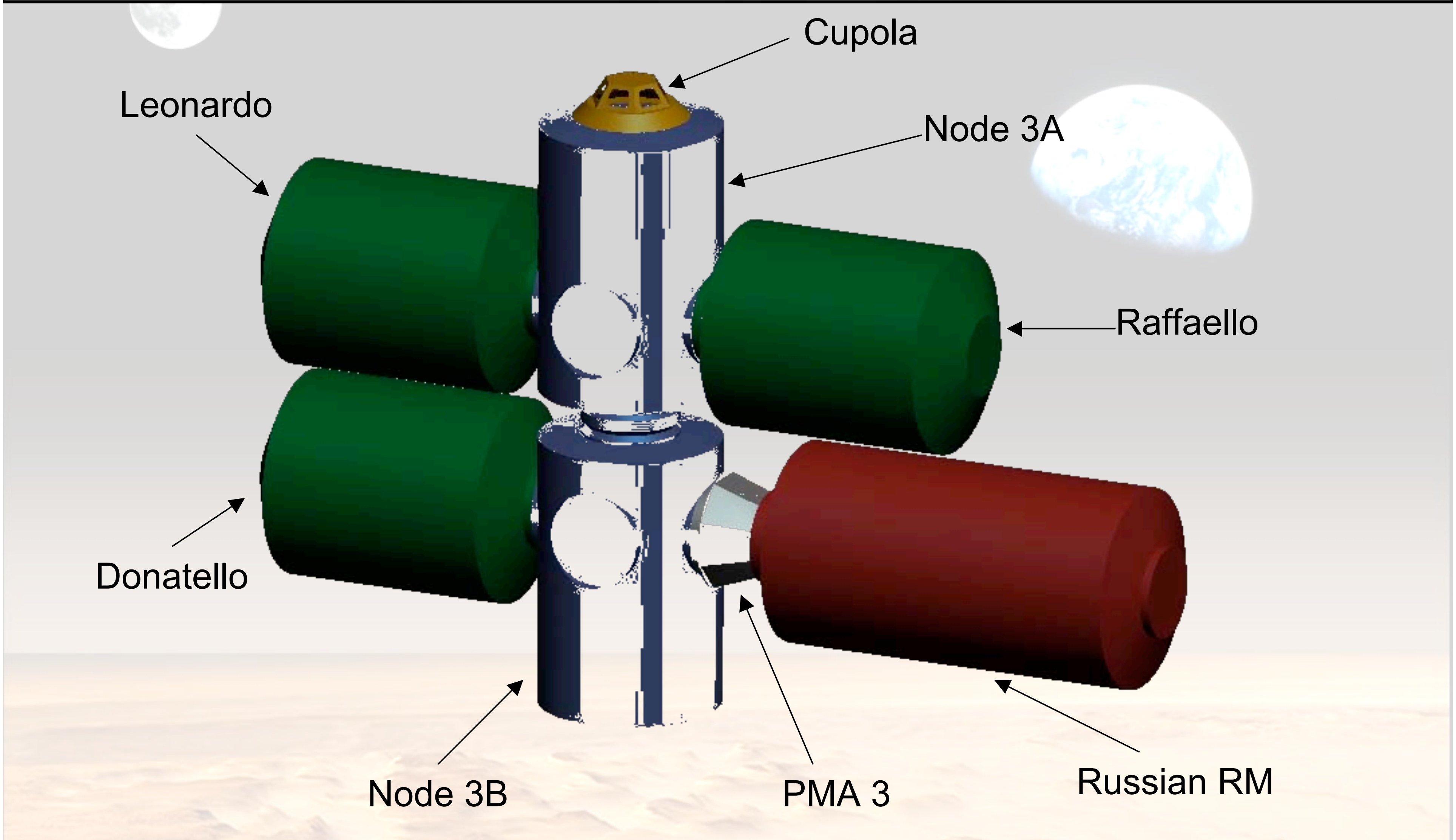
Image: http://www.boeing.com/defense-space

Limits of Construction

- The relationship along the ±X axis is linear; in this case, a 5% window limits construction to a height or depth of ±1.4 m
- Since 1.4 m < cabin height, this eliminated the possibility of a multi-level habitat
- These factors result in the townhouses being restricted to a very specific envelope of construction

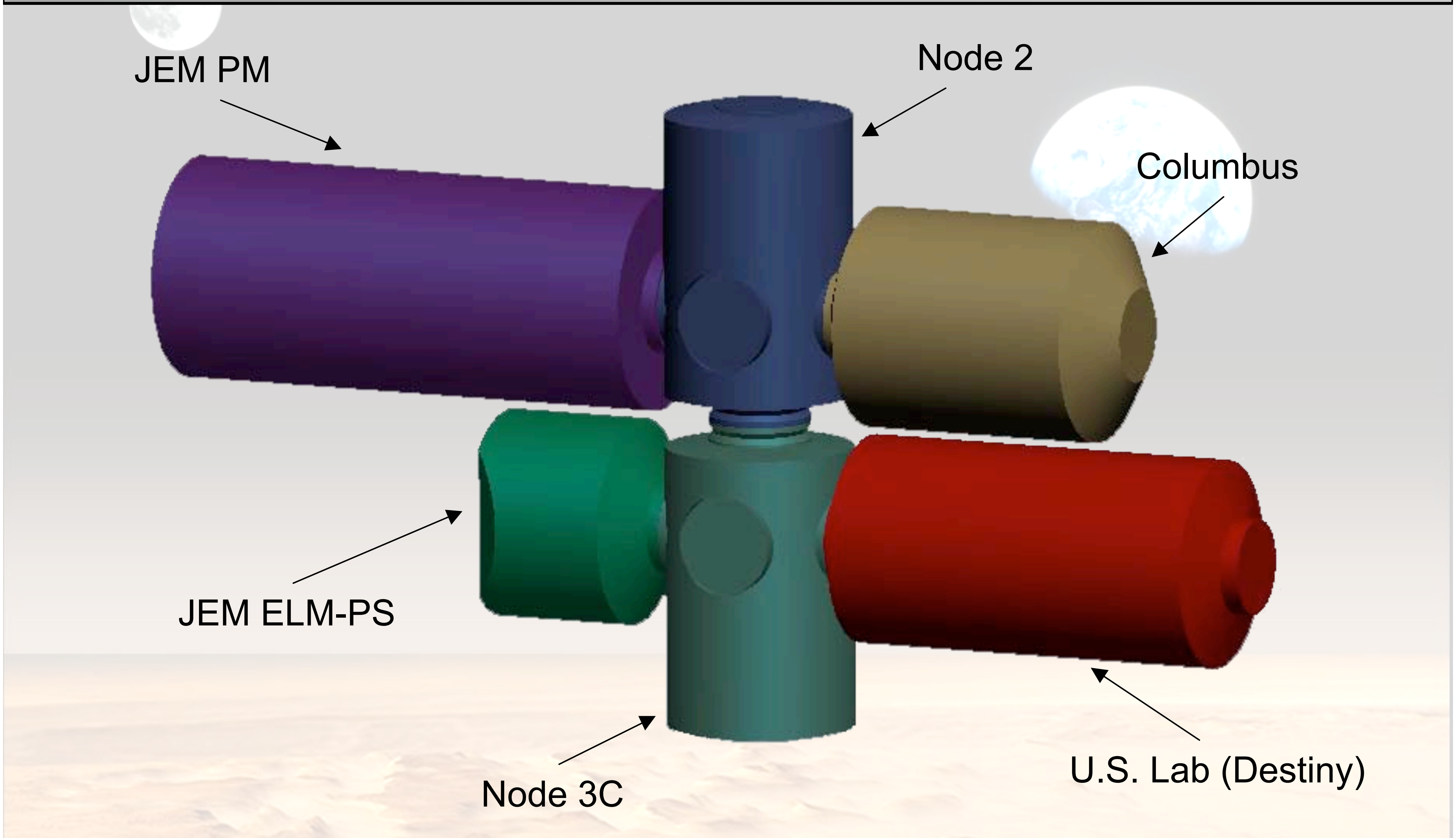


Townhouse A

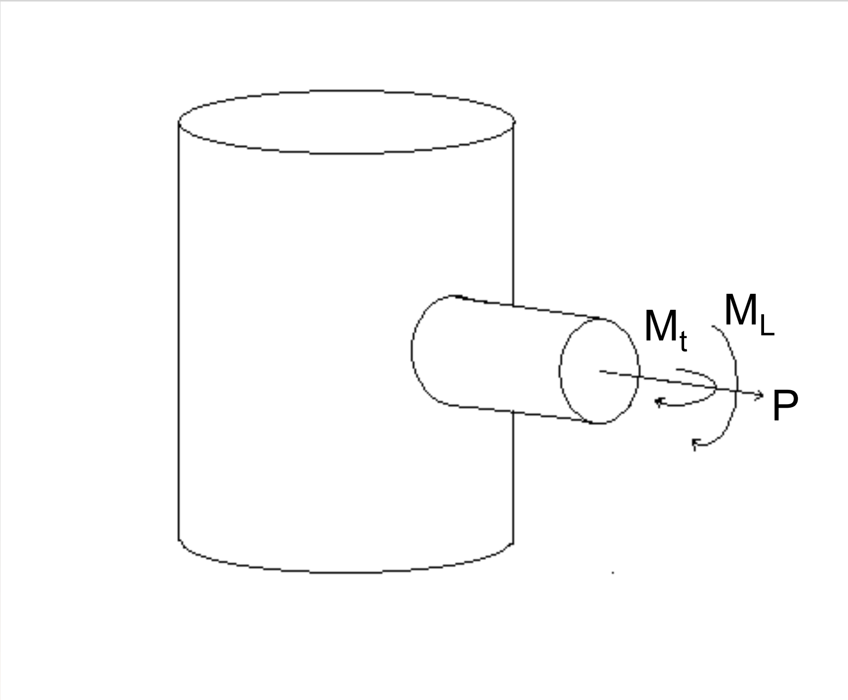


Cupola
Leonardo
Node 3A
Raffaello
Donatello
Node 3B
PMA 3
Russian RM

Townhouse B



Module Loading Analysis



Stress due to tangential moment (M_t)

$$\sigma_t = C_t (M_t / t^2 R\beta)$$

Stress due to Longitudinal moment (M_L)

$$\sigma_L = C_{LL} (M_L / t^2 R\beta)$$

Hoop Stress

$$\sigma_{hoop} = pR / t$$

Stress due to radial load (P)

$$\sigma_p = C_p (P / t^2)$$

Eqns: Bednar's Handbook of Pressure Vessel

Actual loading most likely a combination of longitudinal and tangential

Module Loading Analysis

- Simulate modules connected to nodes as simple cantilevered structure
- Force balance to determine cases of max moment and max reaction from one module at a time

Maximum in yellow

Module	Radius (m)	Length (m)	Mass (kg)	Moment (N)	Reaction Force (N)
Columbus	2.24	6.87	1.93×10^4	6.50×10^5	1.89×10^5
Donatello	2.29	6.40	1.32×10^4	4.13×10^5	1.29×10^5
Leonardo	2.29	6.40	1.32×10^4	4.13×10^5	1.29×10^5
Raffaello	2.29	6.40	1.32×10^4	4.13×10^5	1.29×10^5
US Lab	2.15	8.50	1.45×10^4	6.05×10^5	1.42×10^5
Cupola	1.50	1.50	1.88×10^3	1.38×10^4	1.84×10^4
JEM ELM-PS	2.20	3.90	3.81×10^3	7.29×10^4	3.74×10^4
JEM PM	2.20	11.20	1.59×10^4	8.73×10^5	1.56×10^5
Node 1	2.30	5.50	1.53×10^4	4.13×10^5	1.50×10^5
Node 2	2.24	6.71	1.53×10^4	5.03×10^5	1.50×10^5
Node 3	2.24	6.71	1.55×10^4	5.10×10^5	1.52×10^5

Module Loading Analysis

Worst case moment due to a single module: JEM-PM (8.73 x 10^5)

	Longitudinal	Tangential
Stress from M (Pa)	1.71 x 10^8	6.38 x 10^8
Buckling Strength (Pa)	4.70 x 10^7	4.70 x 10^7
with SF (Pa)	2.35 x 10^7	2.35 x 10^7
Tensile Strength (Pa)	3.52 x 10^8	3.52 x 10^8
with SF (Pa)	1.76 x 10^8	1.76 x 10^8

Node properties	
Internal Pressure (Pa)	1.01 x 10^5
Node Radius (m)	2.30
Berthing Radius (m)	1.20
β	0.457
Cll	0.0750
Ct	0.280
γ	0.00
Node thickness (m)	6.05 x 10^{-3}
Material property	
ν	0.330
E	7.31 x 10^{10}

*Aluminum (Al 2219-T8)

- **Local Buckling Yield Strength**

$$S_y = \frac{E}{\sqrt{3} * \sqrt{(1-v^2)}} \frac{t}{r} \times 40\%$$

(*Ref:* Roark's)

If not reinforced, total stress exceeds yield stresses and failure occurs

Townhouse Deflection

- Townhouses cantilevered from central truss
- Inflatable transfer tube cannot carry any load from townhouse
- Cables employed to:
  - Eliminate loading of inflatables
  - Eliminate moment on townhouse to truss connection
  - Reduce mass of townhouse support structure

Cable Selection

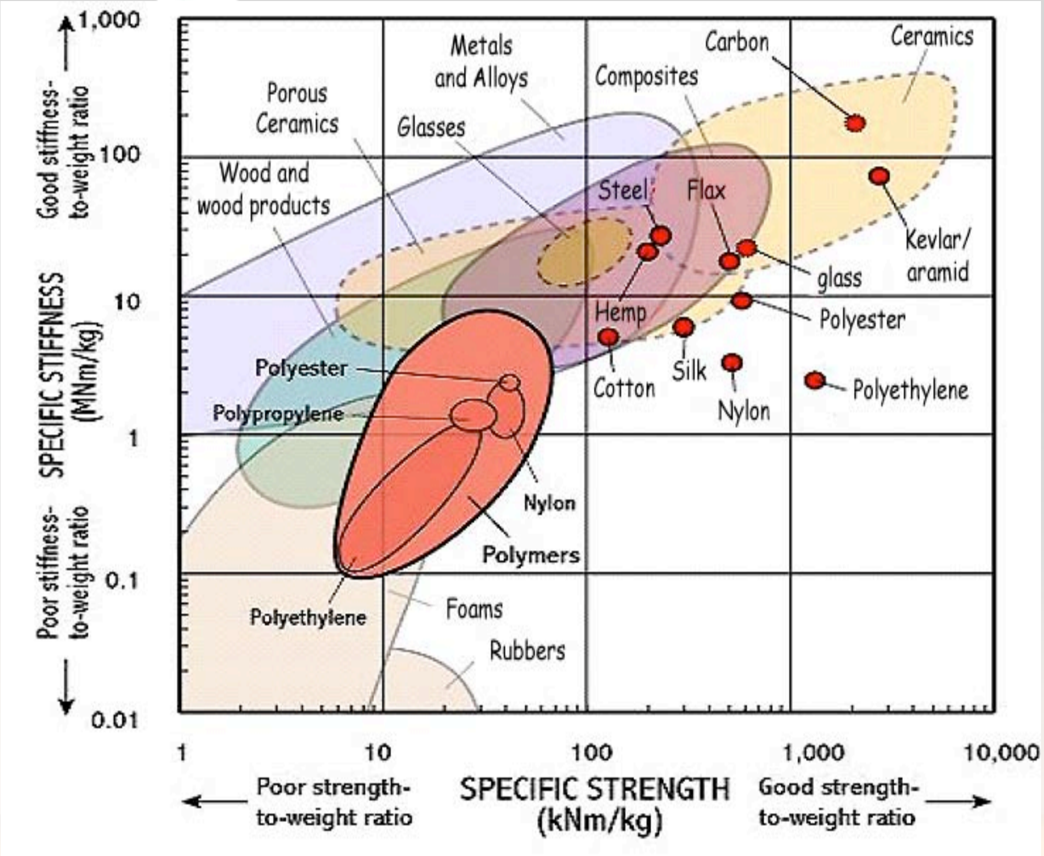


Image: http://www.materials.eng.cam.ac.uk

Aramid Fiber

Young's modulus: 124 GPa

Density: 1,450 kg/m^3

Tensile strength: 3,930 MPa

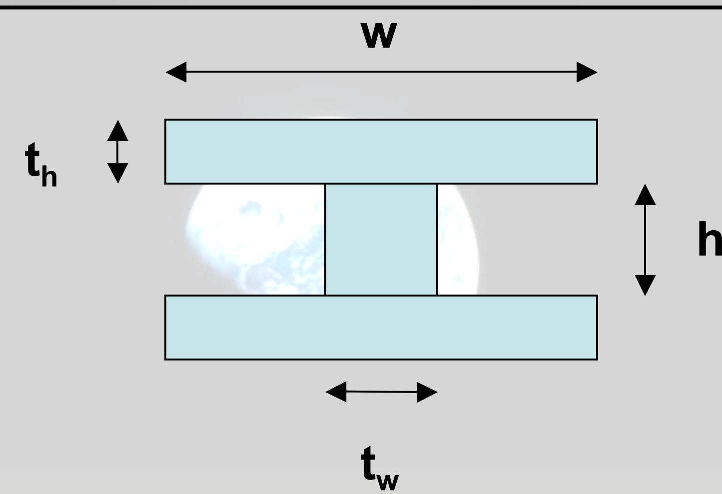
Kevlar/Aramid: Best Specific Strength

Townhouse Support Structure

- Requirements: support the townhouse modules minimizing bending and compression on the module connections Also, connect townhouse to ISS S5/P5
- approach: support with beams to offload bending moments

I-Beam Crossection Design

Strut Support Beam Cross-section Dimensions (m)					
Label	w	t_w	h	t_h	A (m^2)
THASSB1	0.17	0.13	0.24	0.21	0.04
THASSB2	0.16	0.12	0.22	0.20	0.04
THBSSB1	0.17	0.14	0.26	0.23	0.03
THBSSB2	0.13	0.10	0.18	0.16	0.03

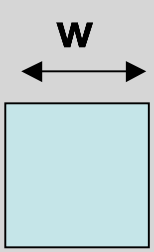


Support Beam Cross-section Dimensions (m)					
Label	w	t_w	h	t_h	A (m^2)
THASB1	0.14	0.11	0.21	0.19	0.08
THASB2	0.16	0.13	0.23	0.21	0.1
THBSB1	0.16	0.12	0.22	0.20	0.09
THBSB2	0.18	0.14	0.26	0.24	0.12

ISS Connection Beam Cross-section Dimensions (m)					
Label	w	t_w	h	t_h	A (m^2)
THAICB1*	0.16	0.12	0.23	0.20	0.09
THAICB2*	0.18	0.13	0.24	0.21	0.11
THBICB1*	0.14	0.10	0.19	0.17	0.07
THBICB2*	0.18	0.14	0.26	0.23	0.12

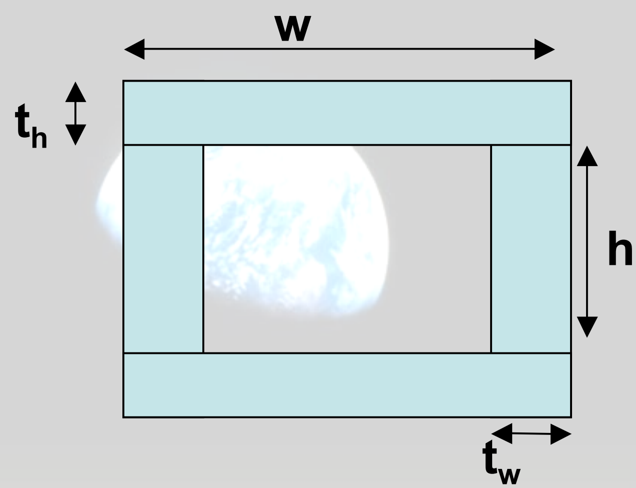
* denotes crossection for configuration with stress relieving cables

Box Beam and Strut Crossections

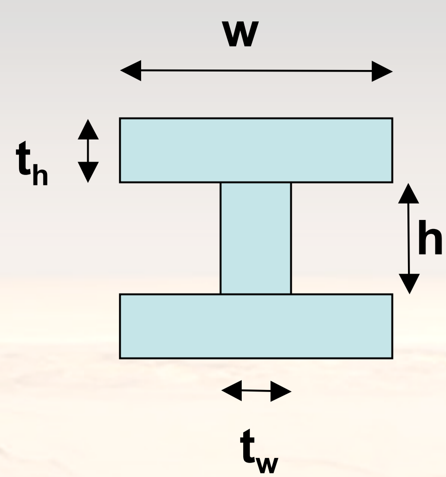


Support Strut Cross-section Dimensions (m)		
Label	w	A (m^2)
THAS1	0.09	0.008
THAS2	0.08	0.006
THAS3	0.09	0.008
THAS4	0.09	0.008
THBS1	0.10	0.010
THBS4	0.12	0.014

Backbone Cross-section Dimensions (m)					
Label	w	t_w	h	t_h	A (m^2)
Backbone A	0.23	0.09	0.44	0.20	0.17
Backbone B	0.17	0.06	0.32	0.15	0.09



Crossbeam Cross-section Dimensions (m)					
Label	w	t_w	h	t_h	A (m^2)
THACB1	0.07	0.04	0.08	0.04	0.01
THACB2	0.06	0.04	0.08	0.04	0.01
THBCB1	0.07	0.05	0.08	0.05	0.01
THBCB2	0.06	0.04	0.08	0.04	0.01

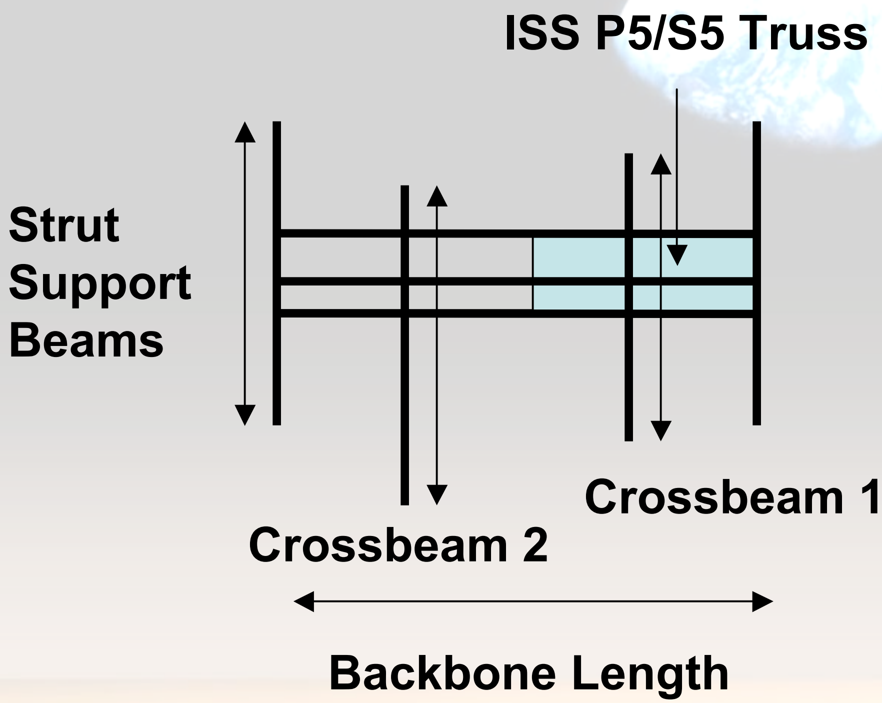


Element Lengths

Support Beam Length (m)
4.68

Crossbeam Lengths	
Label	L (m)
THACB1	19.48
THACB2	17.38
THBCB1	22.68
THBCB2	16.98

Backbone Lengths	
Label	L (m)
Backbone A	13.4
Backbone B	13.4



Material Selection

- 300 series aluminum was selected for its high modulus of elasticity to density ratio
- Material selection made using material properties as specified in MIL-HBK-5H

Material Properties Table		
300 Series Aluminum		
Property	**Value**	**Units**
E	72000	10^3 Kpa
Yeild Stress	152000	Pa
Density	2700	kg/m^2

Mass Table

Table of Masses		
Element Type	**Mass Total**	**% of Basic**
Crossbeams	2000	5
Backbones	9000	25
Support Beams	5000	14
Struts	1000	3
Strut Support Beams	5000	14
ISS Connection Beams*	14000	38
Connections	500	1
Basic Mass Total	***36500***	
Townhouse A Total (10% Margin)	**21000**	
Townhouse B Total (10% Margin)	**19000**	
Total Mass (10% Margin)	**40000**	
% of Total Townhouse Mass	**19**	

Townhouse Cables

- Two cables per townhouse extend from ±Y sides of the connection townhouse to central truss
- Tension sensors monitor tension in each cable
- One control system per cable pair adds or removes tension to cables based on spin rate (to eliminate moment on townhouse connection)
- Cables designed to withstand total tension from townhouse individually (two-fault tolerance if one cable breaks)
  - Safety Factor: 2
  - Max tension: 4.97×10^5
  - Cable diameter: 0.02 m
  - Cable length: 12 m each @ 30º X-Z plane
  - Mass per cable: 4.4 kg

SSP Truss Analysis

- What loads will the truss be under?
- Identify axial loading, tangential loading vibrational loading and moments about all three axis
- Can the truss withstand these loads?

Structure	Mass (kg)
Cupola	1,880
RM	15,715
MPLM	13,154
MPLM	13,154
MPLM	13,154
Node 3	15,500
Node 3	15,500
BB/Spin up	28,375
S5	12,598
S3/4	17,900
S1	15,598
S0	14,970

SSP Truss Analysis (cont.)

Acceleration of SSP due to spin up: Applied load is 24 N in the Y direction at a distance of 50 m

$$a_n = r\omega^2 \qquad a_t = r\acute{a} \qquad V = r\omega \qquad \sum M = I\alpha$$

Maximum Acceleration (m/s^2)	10
Maximum Moment (N·m)	1×10^3

a_n (m/s^2)	a_t (m/s^2)	ω (rad/s^2)	α (rad/s^2)	r (m)
10	2×10^{-4}	0.4	5×10^{-6}	50
8	2×10^{-4}	0.5	5×10^{-6}	40
5	1×10^{-4}	0.5	5×10^{-6}	30
3	7×10^{-5}	0.5	5×10^{-6}	10

SSP Truss Analysis (cont.)

Tangential forces produced by constant angular acceleration at spin up corresponding to the individual components of Townhouse A

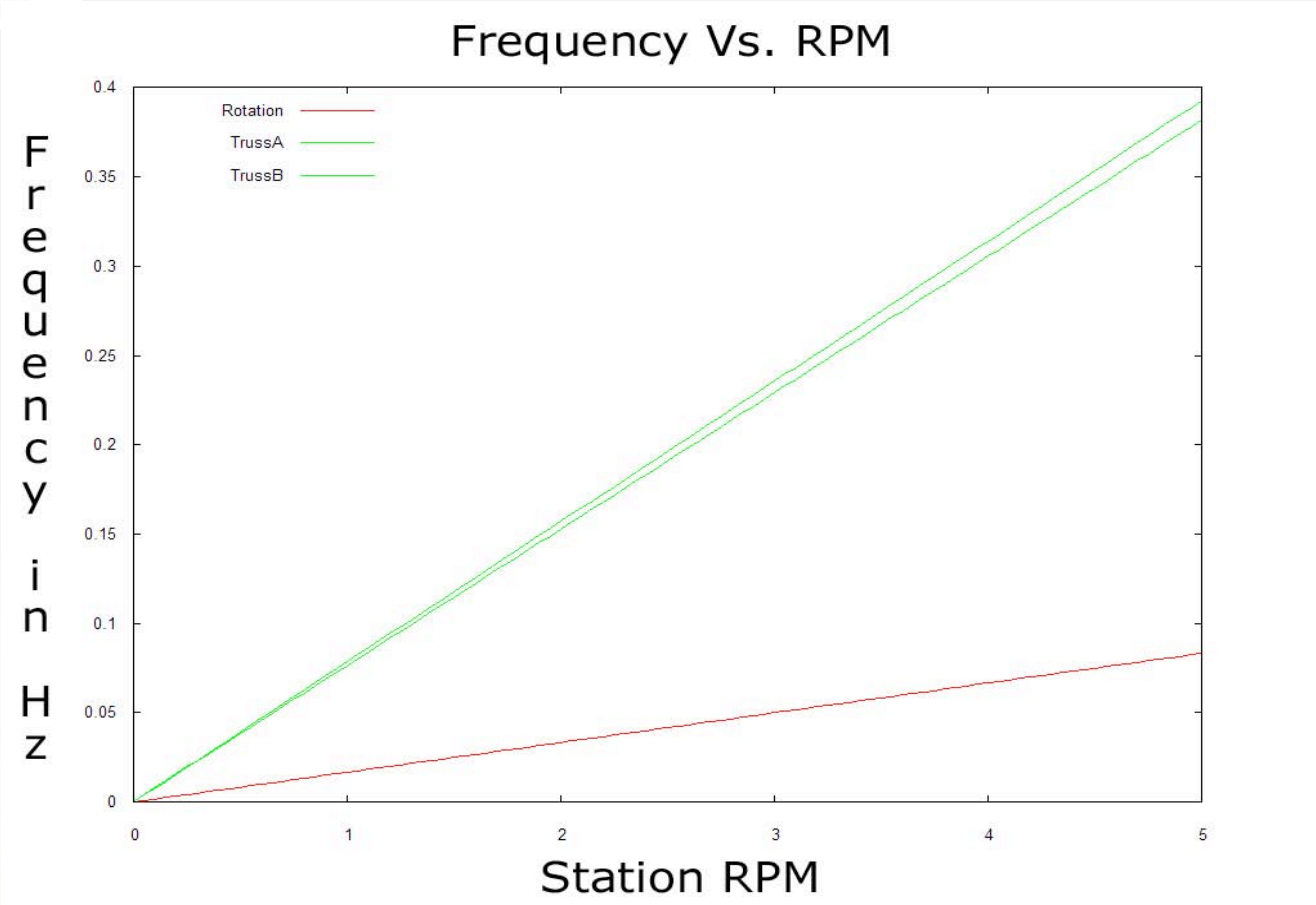
Structure	Tangential Force (N)		
	X	Y	Z
Cupola	0	0.4	0
RM	0	3	0
MPLM	0	3	0
MPLM	0	3	0
MPLM	0	3	0
Node 3	0	3	0
Node 3	0	3	0
BB/Spin up	0	6	0
S5	0	2	0
S3/4	0	2	0
S1	0	1	0
S0	0	0	0

SSP Truss Analysis (cont.)

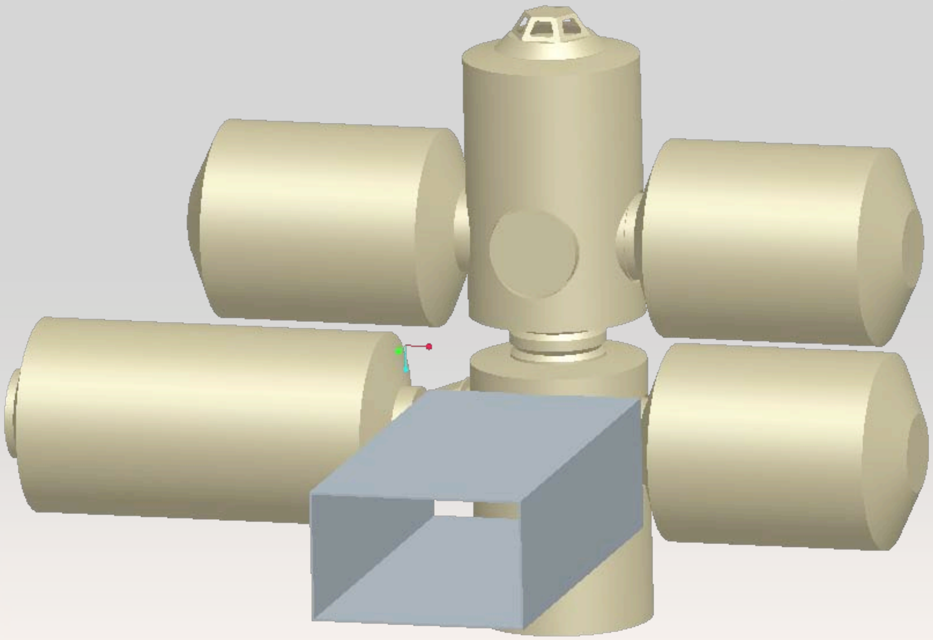
Radial forces produced by a 1g acceleration corresponding to the individual components of Townhouse A

Structure	Radial Forces (N)		
	X	Y	Z
Cupola	2×10^4	0	0
RM	2×10^5	0	0
MPLM	1×10^5	0	0
MPLM	1×10^5	0	0
MPLM	1×10^5	0	0
Node 3	2×10^5	0	0
Node 3	2×10^5	0	0
BB/Spin up	3×10^5	0	0
S5	1×10^5	0	0
S3/4	9×10^4	0	0
S1	4×10^4	0	0
S0	0	0	0

SSP Truss Analysis (cont.)



SSP Truss Analysis (cont.)



Assumptions for modeling the truss:

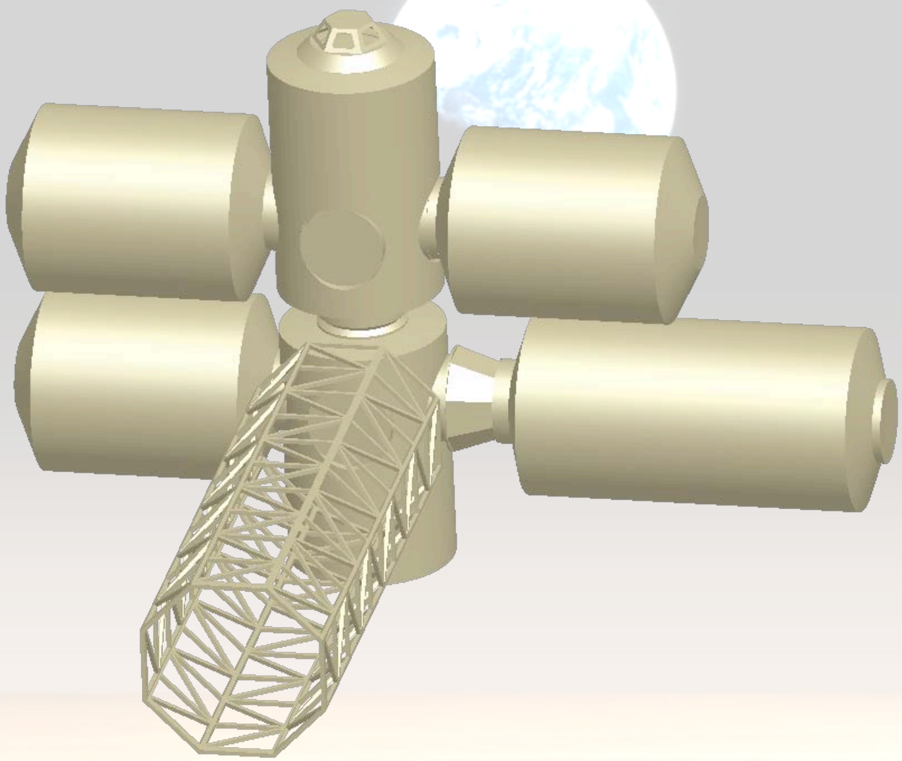
- A rectangular tube with dimensions: H=5 m , B=3 m, t=0.05 m
- Truss is uniform shape and density
- Used Al-7075 characteristics
- Cantilevered beam, fixed at the mid-point of the S0 segment
- Discrete lumped mass corresponding to the geometric center of the component

SSP Truss Analysis (cont.)

Overall Loading Condition:

Total Moments on the truss (N·m)		
M_x	M_y	M_z
1	5×10^4	6×10^7

Radial Force (N)	Tangential Force (N)
P_x	P_y
8×10^6	3×10^1



SSP Truss Analysis (cont.)

9.8 metric Hex bolt (steel)

S_y (Pa)	S_u (Pa)
7.2×10^8	9×10^8

Will truss survive?

Al 7075 Material Properties

E (Pa)	S_u (Pa)	S_y (Pa)	G (Pa)
7.11×10^{10}	5.72×10^8	5.03×10^8	2.69×10^{10}

Dimensions of the truss	
B (m)	5
H (m)	3
t (m)	0.05

Truss Characteristics	
I (m^4)	2.8
Cross-sectional area (m^2)	0.79
EI ($N \cdot m^2$)	2×10^{11}
J (m^4)	2.8

SSP Truss Analysis (cont.)

Tensile Stresses at Bolt Locations (Pa)	
UL	1.06×10^8
UR	1×10^8
LL	-1×10^8
LR	-1.06×10^8

Curvature of the truss (m^{-1})	
M_y	2.5×10^{-7}
Mz	3.0×10^{-4}

Due to M_x	
θ (rad/m)	Shear stress (Pa)
-1.05×10^{-10}	40

Compared to the yield stress of one bolt

S_y (Pa)
7.2×10^8

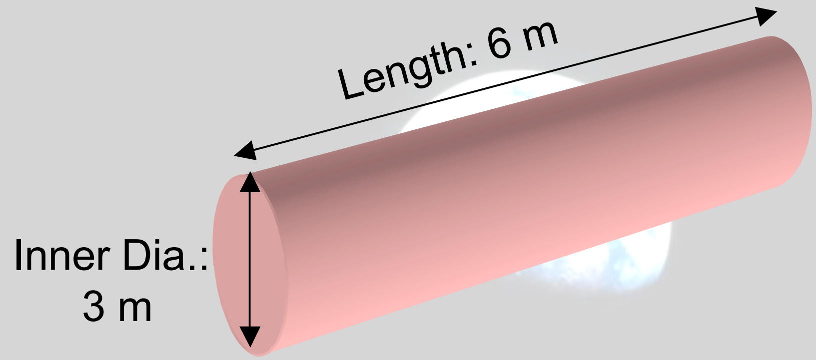
Truss survives

Transfer Tube - Constraints

- 14.7 psi pressure differential
- Inner diameter dependent on exit diameter of Nodes 1 & 3
- Minimize mass / launches
- Shirtsleeve environment for crew transfer between both townhouses

Inflatables for Crew Transfer

- Lower mass than standard aluminum pressure vessel
- Cover 45 m span between townhouses
- Compressed into payload fairing for launch, two sections
- Deployable installation



Test Case: Cylindrical module pressurized to 14.7 psi. SF = 2

Property	Solid (Al 7075)	Inflatable (Kevlar)
Yield Strength	503 MPa	3,620 MPa
Wall Thickness	6.048 mm	0.840 mm
Module Mass	120 kg	8.55 kg

Materials Selection

Standard layering scheme, similar to spacesuits

- Vectran (outer impact)
  2 layers
- Mylar (separation)
  7 layers
- Dacron (volume restraint)
- Urethane-coated Nylon (pressure bladder)

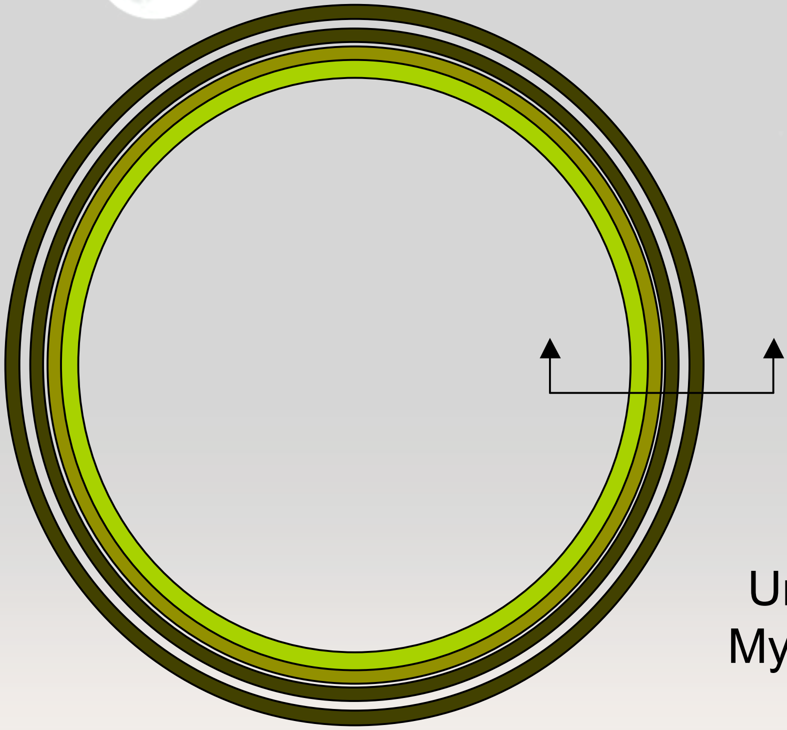
Total interior volume: 163.4 m^3

Total interior surface area: 304.0 m^2

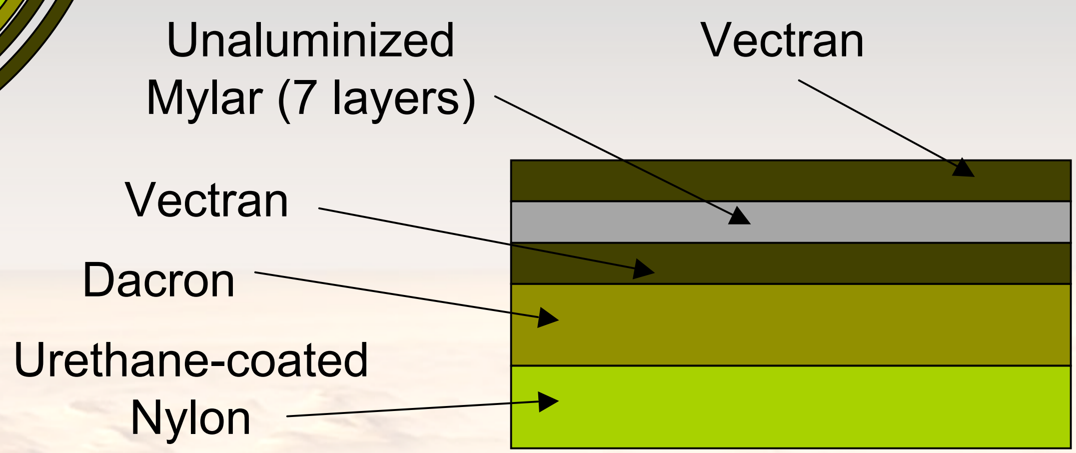
Total softgoods mass: 618.8 kg

Both sections ➡ one launch

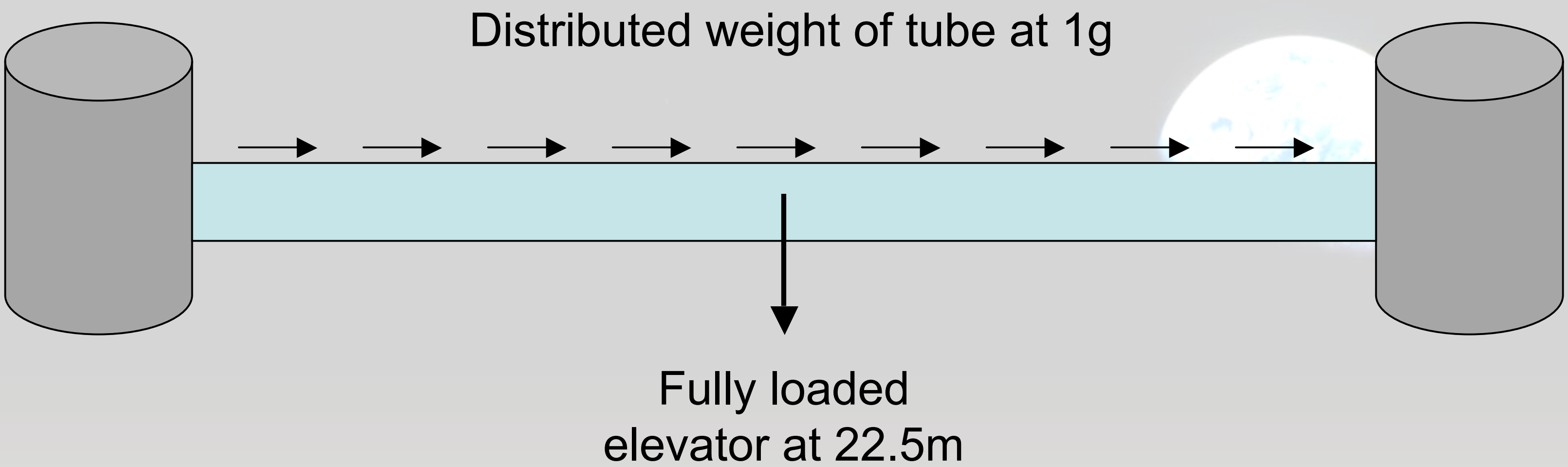
Plying Up



Layer	Thickness (m)
Nylon	0.003
Dacron	0.004
Mylar	0.003 (total)
Vectran	0.002 (each)



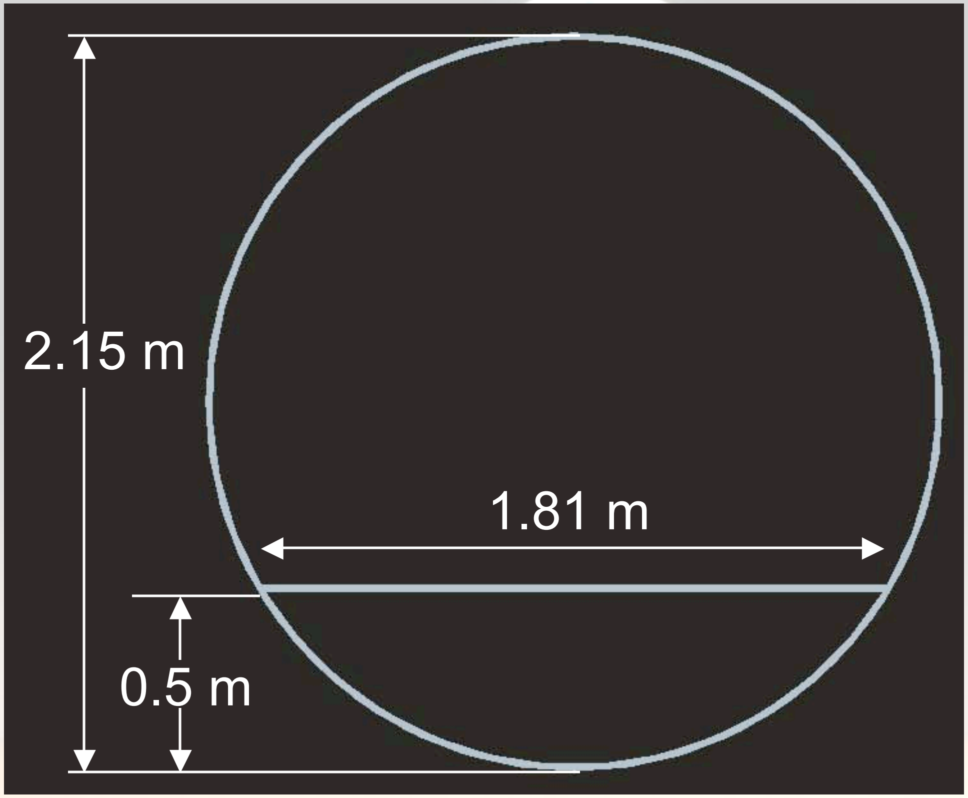
Transfer Tube Support



- Hard point connections every 3 m for interior paneling
- Actual tube does not take spin up/down loads
- Maximum deflection angle less than 0.5° at midpoint (Dacron restraining layer)
- Minimal deflection prevented with aluminum paneling on the tube interior

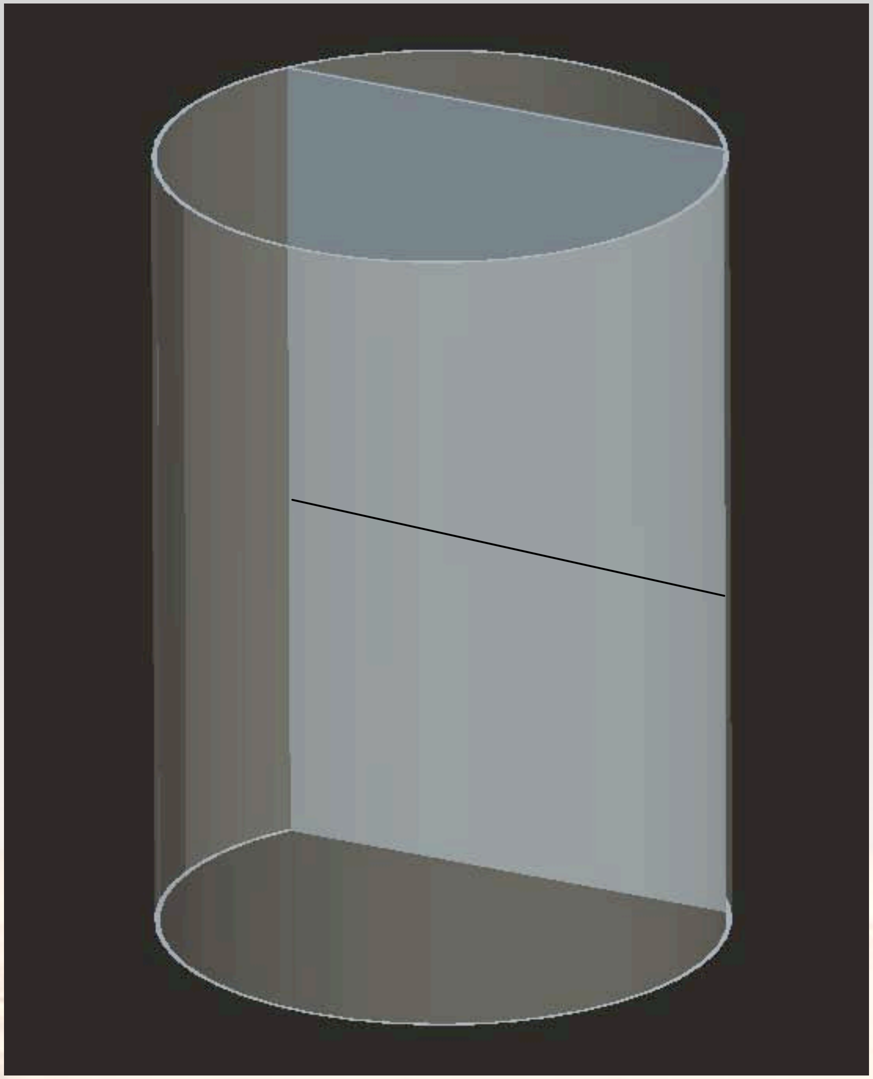
Wall Depth

- Wall depth needs to accommodate ventilation and other life support systems
- Optimal wall depth determined to be 0.5 m
- Given geometry yields a wall width of 1.81 m



Wall Construction

- Foam honeycomb composites chosen for construction
  - Light weight
  - Able to handle deflection
  - Used solely as “dividing” wall
- Panel construction allows for easy access to sub-wall systems
- Attaches via hard-point connections at regular intervals in transfer tube



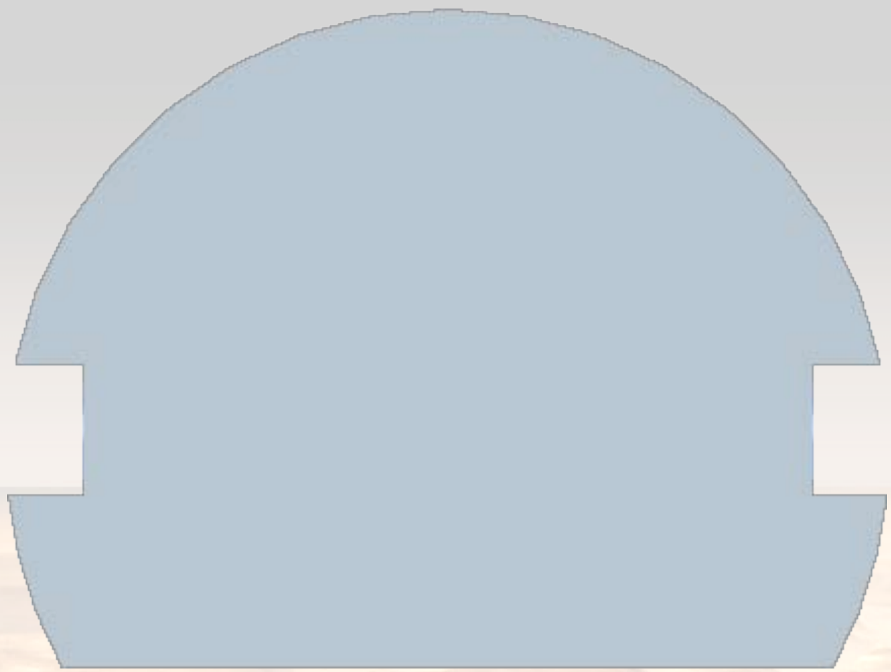
Lifting Mechanism

- Chair lifts designed for home use could be easily modified for use in microgravity
- System has already been designed to have a “low profile”
- Commercial Off the Shelf (COTS) hardware is significantly cheaper than developing new hardware

Credit: http://www.tkaccess.com

Mechanism Modifications

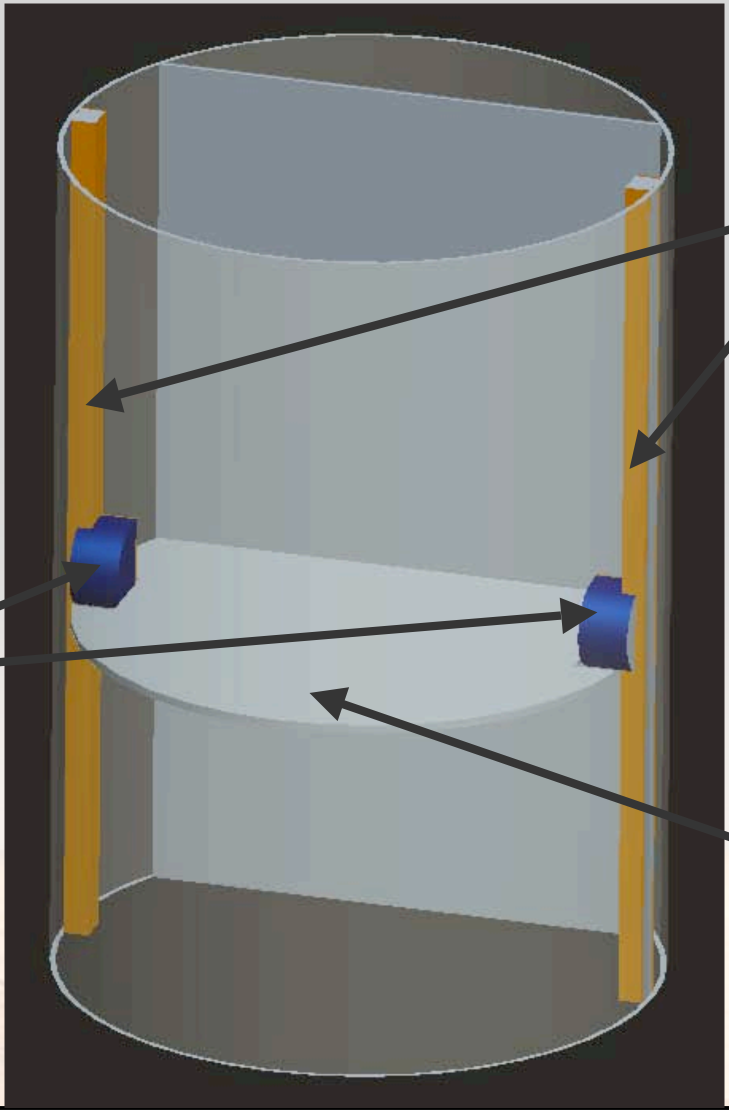
- Consists of two “stripped down” ThyssenKrupp Citia Silver chair lifts with a combined lifting capability of 270 kg (2 crew 95% male crew members + 72 kg of cargo)
- Uses a rack & pinion drive system along tracks offset 180°



•Chairs were removed from lifting systems and replaced by an aluminum honeycomb composite connecting platform (0.05 m clearance from walls)

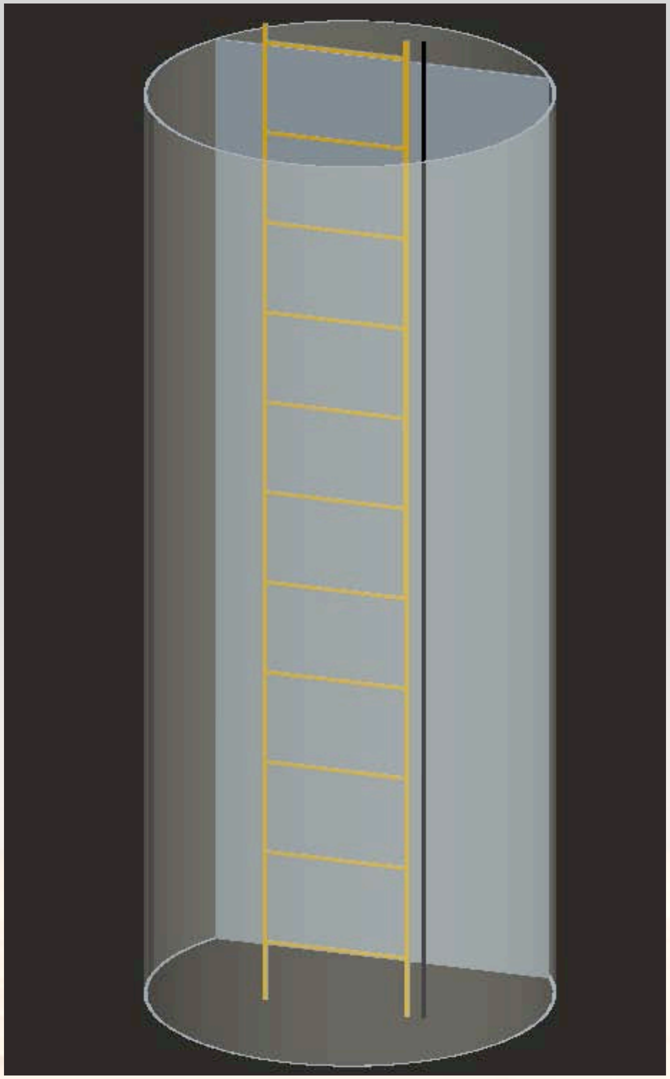
•Onboard restraints can be added for crew safety

Integration



Backup Transport System

- The lift's connecting platform is removed
- A rope ladder is installed by attaching it to the top and bottom of the pressurized tube
- A taut climbing line is attached in parallel to the ladder
- A traditional climbing harness and ascender mechanism is used to assist in installation and ensure crew safety



Micrometeoroid shielding

- Station pressurized modules surface area is 2,940 m^2
- On average there will be 0.05 hits / year from micrometeoroids and orbital debris on a pressurized module from an object larger than 1 cm
- Pressurized station modules are shielded to protect against anything 1 cm or smaller
- Zvezda is not even shielded this much yet

Margin of Safety Table

Module	Safety Factor	Margin of Safety
Townhouse A Support	1.4	0.50
Townhouse B Support	1.4	0.50
Townhouse Cables	1.4	1.86
Inflatable	1.4	0.43
Stability Arm Support	1.4	0.43

Center of Gravity

- On the X axis, the center of gravity is currently 0.50 m towards townhouse B
- On the Y axis, the center of gravity is currently 0.05 m towards the MLM
- Distances are on the same order of magnitude as measurement uncertainty
- Center of gravity on Z axis is at 4.12 m below the center of Node 1

Moments of Inertia

Geometric axes, rotating section only

3.20 x 10^7	-2.49 x 10^6	-4.43 x 10^6
-2.49 x 10^6	**4.54 x 10^8**	-8.38 x 10^4
-4.43 x 10^6	-8.38 x 10^4	**4.67 x 10^8**

3.20 x 10^7	0	0
0	4.54 x 10^8	0
0	0	4.67 x 10^8

Principal axes – these axes are within 1° of the geometric axes

Evaluating Stability

- Considerations:
  - For $I_{ZZ}>I_{YY}>I_{XX}$, stable if spun about the Z or X axes
  - If spin axis is not exactly along the Z-principal axis, the angular velocity vector will nutate
  - Nutation will arise if:
    - Spin-up thruster angles are off
    - Principal and geometric axes are different
  - Nutation due to spin-up thruster inaccuracies can be eliminated through active or passive damping
  - Nutation due to misalignment of axes can be eliminated for short durations through active control

Instability Issues

- Incapable of attaining perfect stability indefinitely because I_{XY},I_{XZ}, and I_{YZ} in the inertia tensor are not zero
- Instead, seek to limit instability to levels which do not impede functionality
- Nutation causes:
  - Horizontal acceleration of the “ground” in the human’s reference frame
  - Inertial cap acceleration (the inertial caps, by definition, should not accelerate)
- Functional levels:
  - Horizontal ground acceleration is imperceptible to humans below 0.001g
  - Communications: less than 2° of nutation
  - Docking: 0° of nutation

Stability Calculations

Assume:

- Spin-up thruster angles are known to within 1°
- Principal axes are 0.643° off geometric axes
- ¾g artificial gravity operating conditions
- No active or passive damping (controls analysis difficult)

Stability Calculations

- It would be best to determine the station's dynamics through an analytical solution to Euler's equations
- Euler's equations become non-linear when $I_{XX} \neq I_{YY}$ (where Z is the spin axis)
- Solution is to evaluate station's dynamics numerically
  - Simulation time step: 0.05 s
  - Simulation length: 100 s

SSP Performance

- Transient periods (after thruster firings):
  - Maximum ground acceleration:
    58% perceptible levels
  - Maximum inertial truss angular deflection:
    3.8°
  - Frequency of truss deflection:
    0.09 Hz
- Steady-state operation:
  - Maximum ground acceleration:
    23% perceptible levels
  - Maximum inertial truss angular deflection:
    1.9°
  - Frequency of truss deflection:
    0.06 Hz

Final Assessment

- At all times:
  - Horizontal ground accelerations will be imperceptible
- Transient periods:
  - Back-up communications will be used
- Steady-state:
  - Active control will accompany docking and enable stable operation for short durations

Spinning

- 8 thrusters will be used for spinning
  - 4 for spin-up, 4 for spin-down
- Thrusters will be mounted in two areas
  - 4 thrusters on the outside of each townhouse section
    - 2 thrusters in each direction
- Will require 80 kW of power

Spinning (cont.)

Spin times:

Desired Gravity	Current Gravity	Time to Spin
⅜g	0g	6.9 hours
¼g	0g	5.7 hours
½g	¼g	2.4 hours
¾g	½g	1.8 hours
0g	¾g	9.8 hours

Orbit Maintenance

- 10 thrusters used for orbit maintenance
  - 5 thrusters on each end of the central axis
    - 2 pointed in X-direction, 2 pointed in Y-direction, 1 pointed in outward Z-direction
- Station keeping will be done continuously
  - Base ΔV of 55 m/s each year
  - Drag compensation is 25 m/s each year
    - Total ΔV of 80 m/s each year requires 1.14 N of continuous thrust
    - Requires 2 kW of power

P&W T-220HT

- Hall-Effect Thruster
- Specific Impulse (I_{SP}) of 2,500 s
  - High I_{SP} saves over 80% on propellant mass vs. chemical propulsion system

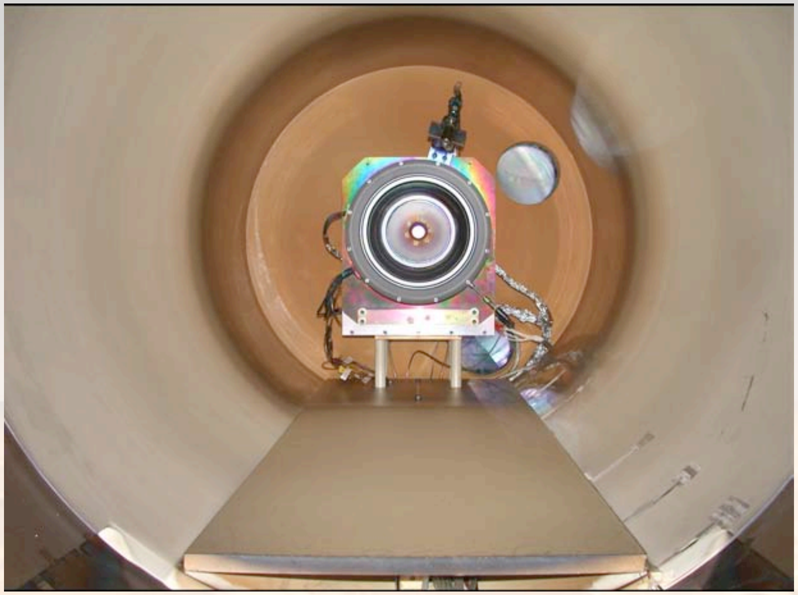
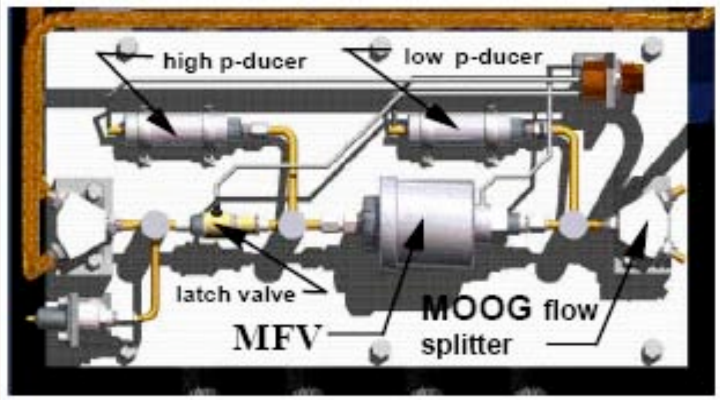


Image: Characteristics of the T-220HT Hall-Effect Thruster (Britt, McVey) 2003



Propellant Delivery System for T-220HT

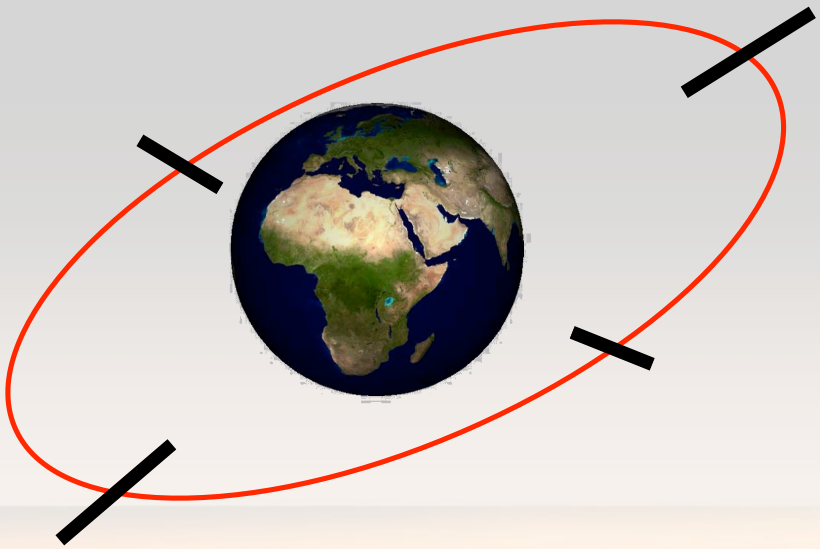
Image: Electric Propulsion Activities In U.S. Industries (Britt,McVey) 2002

P&W T-220HT (cont.)

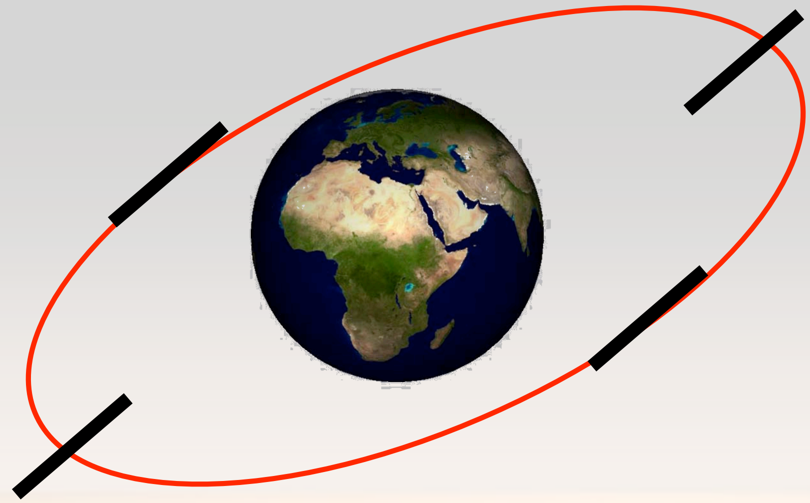
- Delivers thrust at 0.6 N/kW
  - Rated to a maximum of 22 kW
  - Will be used at a maximum of 12 N on SSP
- Exhaust plume exits with a 28° half-angle
  - At 1 m the plume is less than 200 °C
- Liquid xenon will be propellant
- 18 thrusters will be used for spinning, station keeping, and attitude control

Orientation Options

- Processing orientation



- Inertial orientation



Processing Orientation

- Requires only one communication dish for full coverage
- Spin direction pointing toward Earth makes gravity gradient perturbations negligible

- Does not allow for adequate sun exposure for solar arrays
- Requires the a precession rate of (360° / 91 min)
- ~2,400 kg of propellant every revolution using electrical thrusters

Inertial Orientation

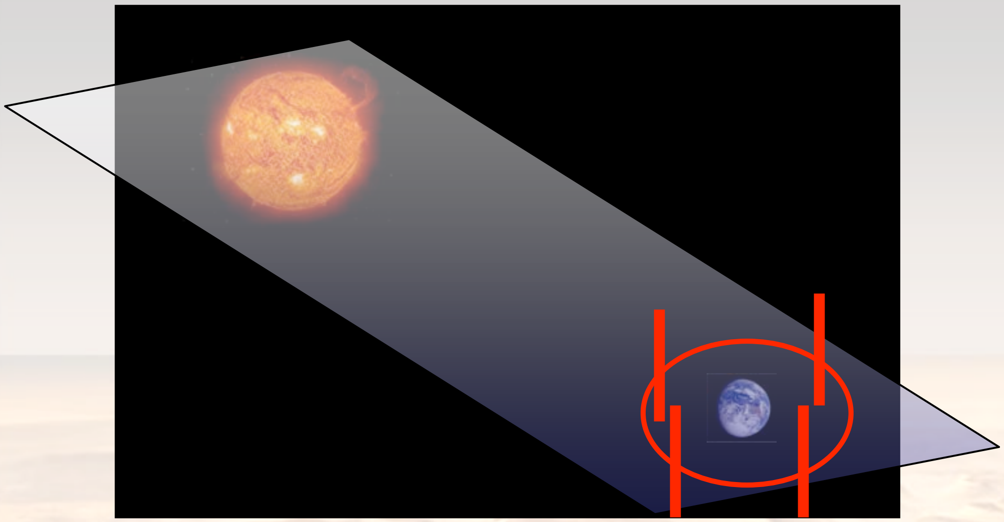
- Allows for constant solar array sun exposure in conjuncture with gimbaled solar arrays
- Requires a precession rate around the sun for inertial caps for solar array pointing

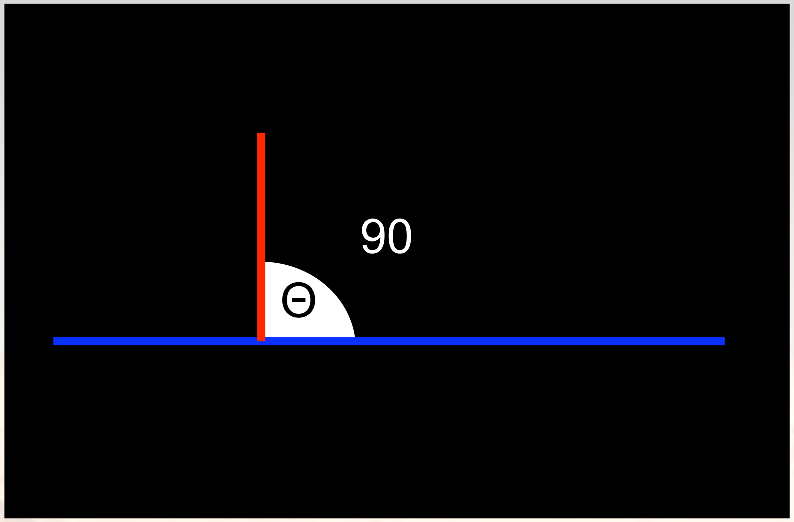
  (1.14 x 10^{-5} rad/s)

- Requires at least two communication dishes for full coverage
- Gravity gradient perturbations affect orbit (~40 kg/yr of propellant)

Inertial Angle

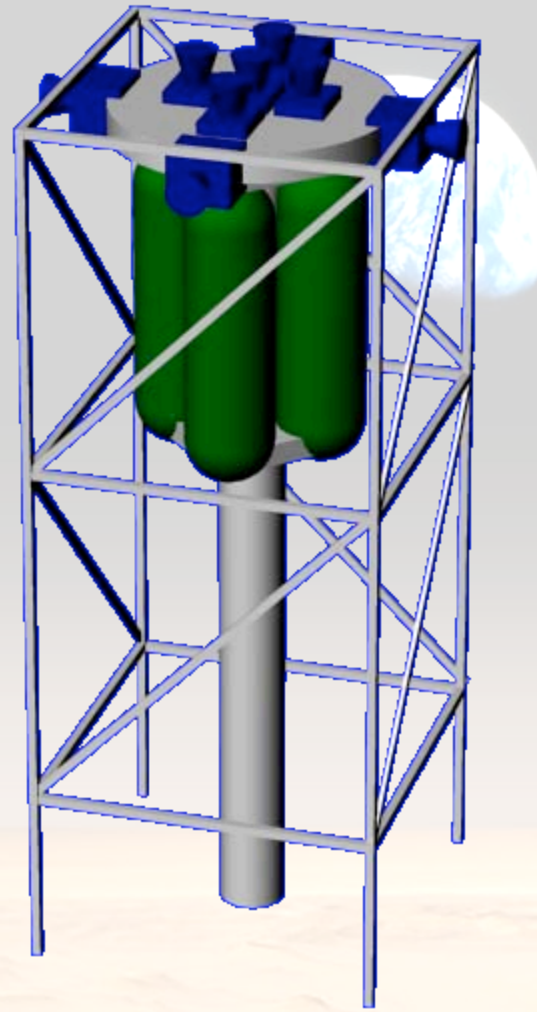
- What angle should the rotation axis be in regards to the Sun-Earth plane?
- As Earth rotates and Θ increases, less solar array pointing is required





ACP Truss

- Attitude Control Propulsion Truss
  – Attitude electrical thrusters
  – Xenon tanks
  – Xenon propellant
  – Bottom ACP will hold more propellant because of orbit maintenance purposes



ISS Attitude Control Components

- Control Moment Gyros (CMG)
  - 4 CMGs mounted along central axis
  - Constantly seek Torque Equilibrium Attitude (TEA)
  - When net torque on station is non-zero, CMGs begin to saturate
  - Since SSP needs to hold constant pointing angle to sun, which requires a constant torque, CMGs would saturate rapidly (~30 s) and are not a feasible method of attitude control
- Reaction Control Thrusters
  - Both U.S. and Russian systems use chemical thrusters of various thrust capabilities
  - Used for attitude maneuvers and fired to desaturate CMGs

Perturbations

- Magnetic field force

    Must be considered due to being within Van Allen Belts

- Solar radiation pressure

    Function of sun distance, exposed area, surface reflectivity, and center of solar pressure distance from center of mass

- Atmospheric drag

    Does not affect attitude control, only a factor for translational motion

Perturbations (cont.)

Station deflection due to perturbations

- SSP will realign to desired orientation whenever offset by more than 2°
- This method uses less xenon mass than waiting for larger offset and then realigning
- Requires more xenon mass to realign while spinning than while not spinning
- Far fewer realignments needed while spinning than while not spinning due to high angular momentum of the station

Perturbations (cont.)

- Station requires 21.5 kg/yr to control attitude while spinning
- Station requires 613 kg/yr to control attitude while not spinning
- Station is kept spinning except for when it is necessary to simulate 0g for the Mars transfer mission

Docking Perturbations

- Torque due to docking is a function of distance from center of mass to docking port and force imparted from CEV to station during dock
- Docking torque
  - CEV and payload assumed to be ~30,000 kg and decelerates from 2.24 m/s to rest in 1 s for a force of ~66 kN
  - To realign after a dock requires 5.5 kg of xenon while spinning
  - Realignment requires 1.0 kg of xenon while not spinning

Docking Stability

- Station is stable within operating margins, but needs to be at a higher stability level during docking maneuvers
- Requires large torques for short durations prior to dock, but only while station is spinning
- Required torque is too high for electric thrusters to produce
- Reuse ISS chemical thrusters and tanks and mount them along Z axis
- Will require 1,250 kg of propellant (N_2O_4 / MMH)

Xenon

Xenon mass use:

Maneuver	Mass Required	
Spinning	310 kg	
Perturbations	715 kg	
Station Keeping	8,900 kg	
Docking	780 kg	With 30% Margin
Total	11,000 kg	**14,000 kg**

Tanks

4 tanks used to store liquid xenon

- Each tank at 900 psi
- 2 tanks for spinning
  - 1 tank mounted with each thruster package
  - Each tank approximately 175 kg (including xenon)
- 2 tanks for orbit maintenance/attitude control
  - One tank mounted on each end of the central axis
  - Top tank approximately 1,100 kg (including xenon)
  - Bottom tank approximately 14,000 kg (all xenon for orbit maintenance)

State Determination

- ISS current method:

  2 Receiver/Processor (R/P) sensors in Destiny access GPS data (supplemented by GLONASS R/P data from Zvezda)

- Both are available for use on SSP following R/P sensor movement to the inertial trusses

Attitude/Rate Determination

- ISS current method:
  - Primary (Destiny): Interferometry of GPS signals using 4 GPS antennas (attitude) and 2 RGAs, each containing 3 RLGs (attitude rate)
  - Secondary (Zvezda): 3 star mappers, 4 Sun sensors, 3 Earth horizon sensors, 2 magnetometers (attitude), and 4 RLGs (attitude rate)
- GPS antennas are moved to the ends of SSP solar arrays
- All secondary attitude sensors are incapable of functioning on SSP due to nutation
- RLGs must be moved to SSP center of gravity

Powering the Station

Power will be provided to the station via two systems:

- Solar panels
  - Main supply of all power for the station
  - Used to recharge batteries
- Batteries
  - Will power the station during eclipse periods
  - Will provide emergency power

Sun Exposure

- In LEO, the station will be in sunlight only 60% of each orbit
- Batteries must be sized to power the entire station for 40% of each orbit
- Solar panels must fully recharge batteries during non-eclipse times in addition to powering the station

Power Breakdown

Power for electric thrusters

- Electric thrusters demand excessive power, but are used infrequently at full power

Options for powering electric thrusters

- Oversized batteries
  - Too much energy needed; impractical because of large mass
- Oversized solar panels
  - Lightweight and cost effective

Power Breakdown (cont.)

Overcoming high power consumption

- Attitude control thrusters and spin up thrusters share the same power allotment
- Attitude control thrusters and spin up thrusters will never be used simultaneously
- This saves 45 kW of power compared to each system having a separate power allotment

Solar Panels

- SLASR (Stretched Lens Array Squarerigger) solar panels
- Stretched Lens Array is the blanket which is produced by ENTECH, Inc.
- Squarerigger is the solar array structure produced by ABLE Engineering, Inc.

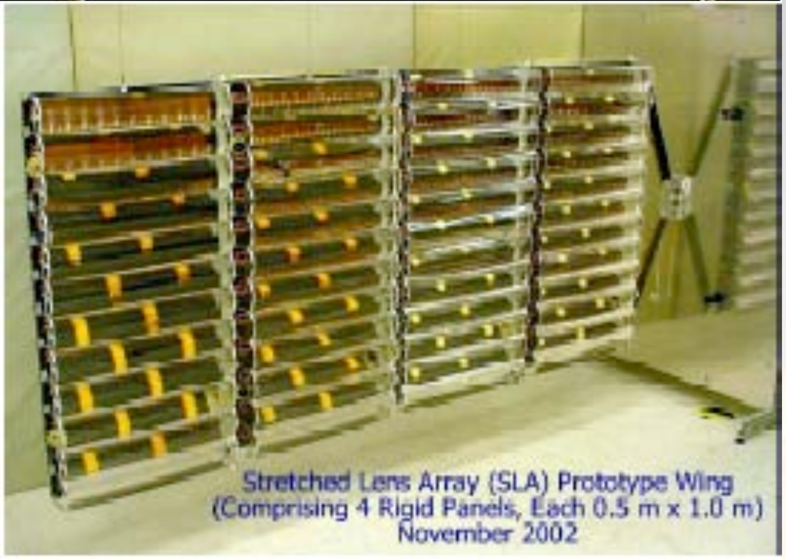
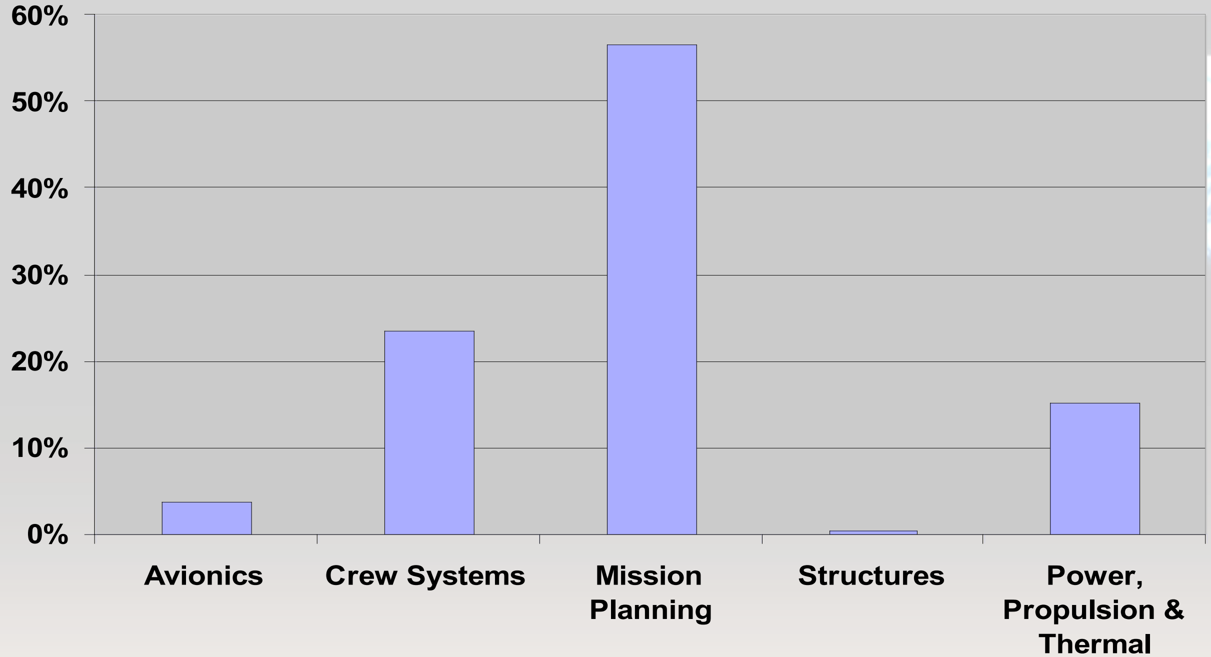


Image: ENTECH, Inc.

Power Budget



- Maximum power needs:
  - Spin up → 80 kW
  - Orbit Maintenance & Attitude Control → 40 kW
  - Everyday needs → 78 kW

Solar Panel Sizing

Power needed for station	158 kW
Power needed to charge batteries	130 kW
Total power the solar panels generate (EOL)	294 kW
Mass of solar panels	1,275 kg
Total area of solar panels	1,400 m^2

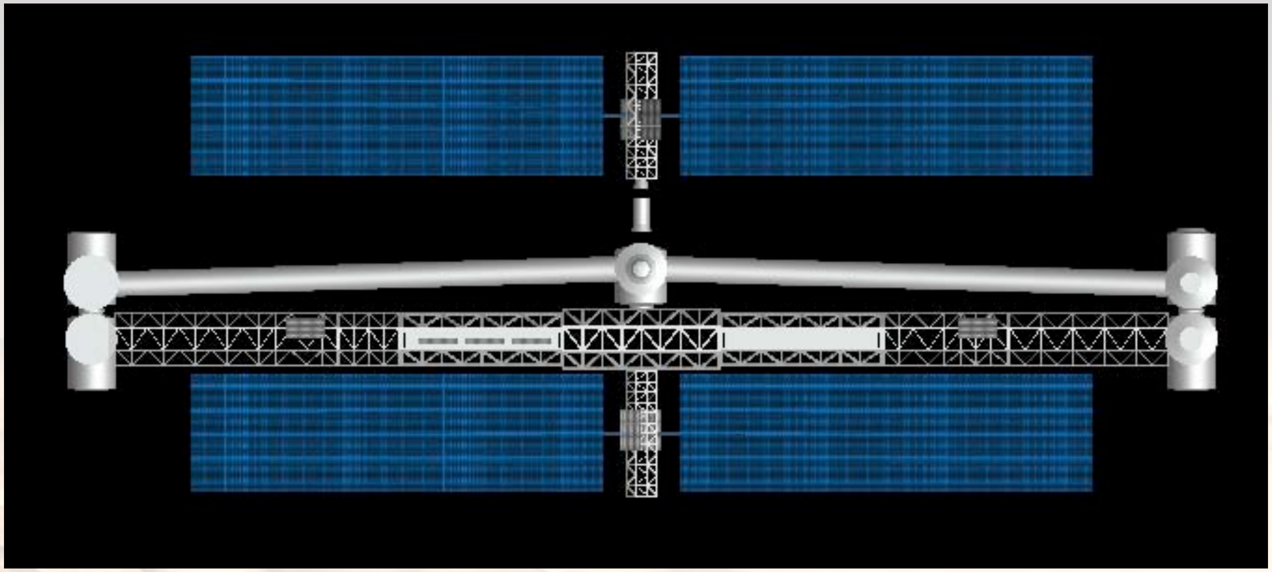
Solar Panel Sizing (cont.)

Solar arrays assembled in building blocks

- Each 2.5 m x 5.0 m bay (or building block) produces 3.75 kW (BOL)
- Number of bays based on power needed
- Bays are assembled to form a rectangle of appropriate size when deployed

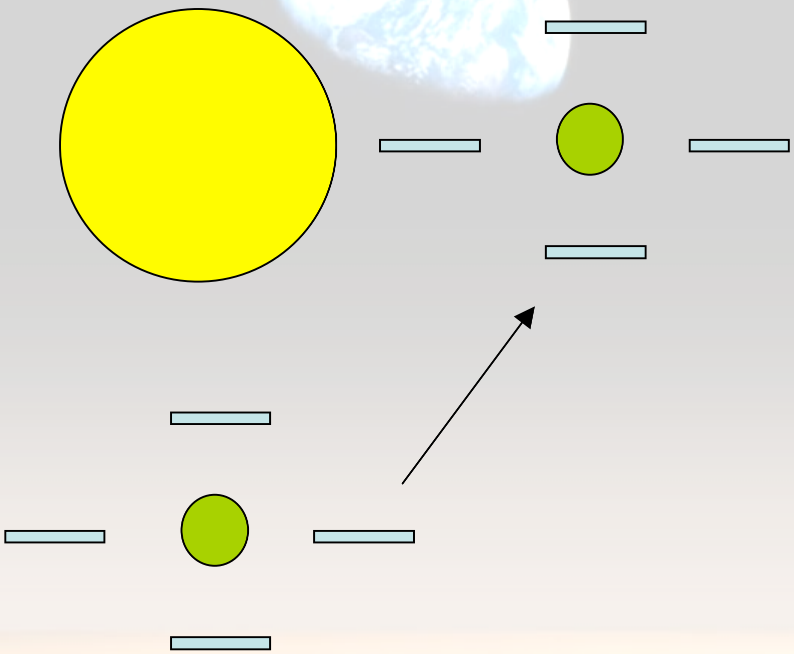
Solar Panel Location

- Solar panels will not rotate with the station in order to maintain maximum sun exposure
- They will be mounted on the upper and lower non-rotating trusses
- Four total array sections, two on each truss



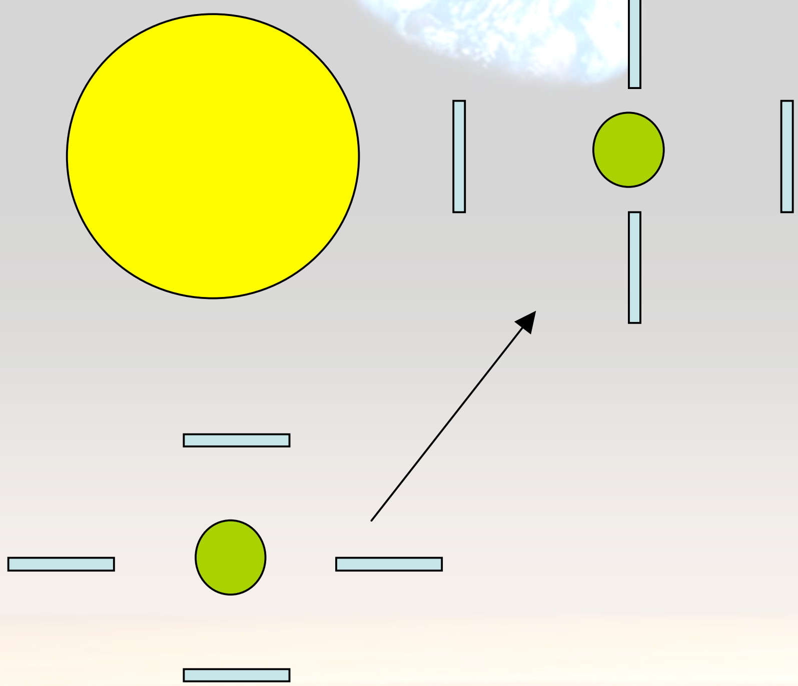
Optimal Sun Alignment

- Solar panel alignment with the sun must be adjusted for optimal sun exposure
- With no adjustment the panels would not remain faced towards the sun



Optimal Sun Alignment (cont.)

- Panels adjusted once per day
- Panels must be rotated 360˚ per year, so the daily adjustment will be 0.99˚



Battery Sizing

- Sizing parameters:
  - 90% efficiency at storing energy and producing power
  - 40% depth of discharge
- Total battery mass : 3,330 kg
- Type of battery to be used:
  - $Ni\text{-}H_2$ batteries in single pressure vessels

Power Margin

- Neither spin up thrusters nor high power attitude control thrusters are operating at most times
- When this occurs, only 208 kW max is being used, while solar panels are optimally producing 294 kW for SSP
- 29% power margin

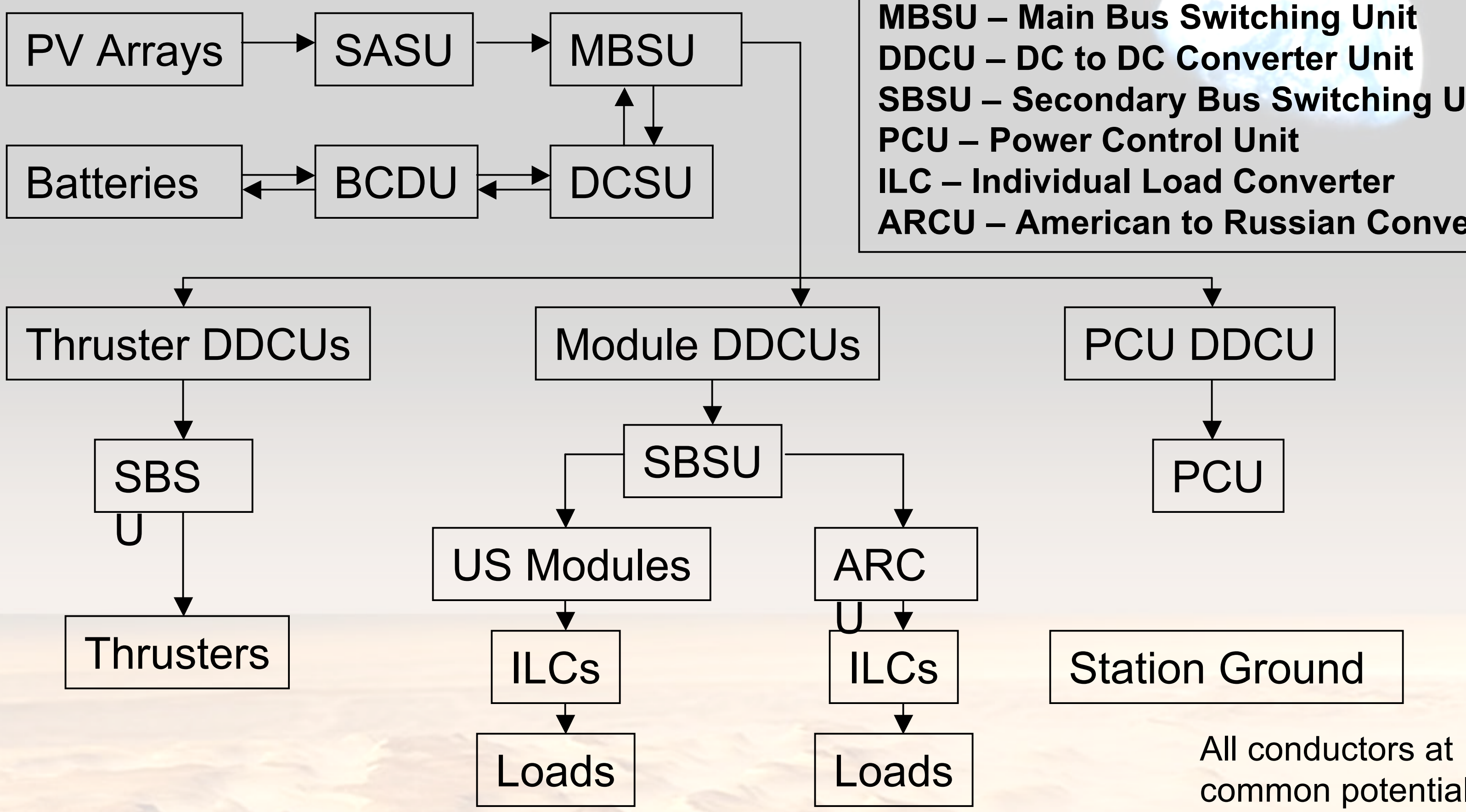
PMAD

Power Management and Distribution (PMAD)

- Generation and storage
  - Solar panels
  - Batteries
- Delivery
  - Power modulation
  - Wiring network
- Grounding

PMAD (cont.)

PMAD Block Diagram



PV – Photo Voltaic Arrays
SASU – Solar Array Switching Unit
BCDU – Battery Charge Discharge Unit
DCSU – DC Switching Unit
MBSU – Main Bus Switching Unit
DDCU – DC to DC Converter Unit
SBSU – Secondary Bus Switching Unit
PCU – Power Control Unit
ILC – Individual Load Converter
ARCU – American to Russian Converter Unit

PMAD (cont.)

- Power Control Unit (PCU)
  - Located in Node rack
  - Directly controls switching units and BCDUs
- Switching Units (MBSU,SASU,DCSU,SBSU)
  - Controls power flow (delivery levels)
  - Physical switches (on/off)
  - Fuses
- Battery Charge Discharge Unit (BCDU)
  - One for each battery
  - Controls power into and out of grid as needed

PMAD (cont.)

Grounding:

- Solar arrays charge station
- Hall thrusters gain charge through operation
- These charges can cause dangerous arcing
- To ensure that this doesn't happen, all surfaces of SSP must be electrically connected. This prevents voltage potentials building up differentially on any one part of the station
- During docking maneuvers, a system of brushes will safely dissipate the charge potential between the incoming vehicle and the station before physical contact between vehicles

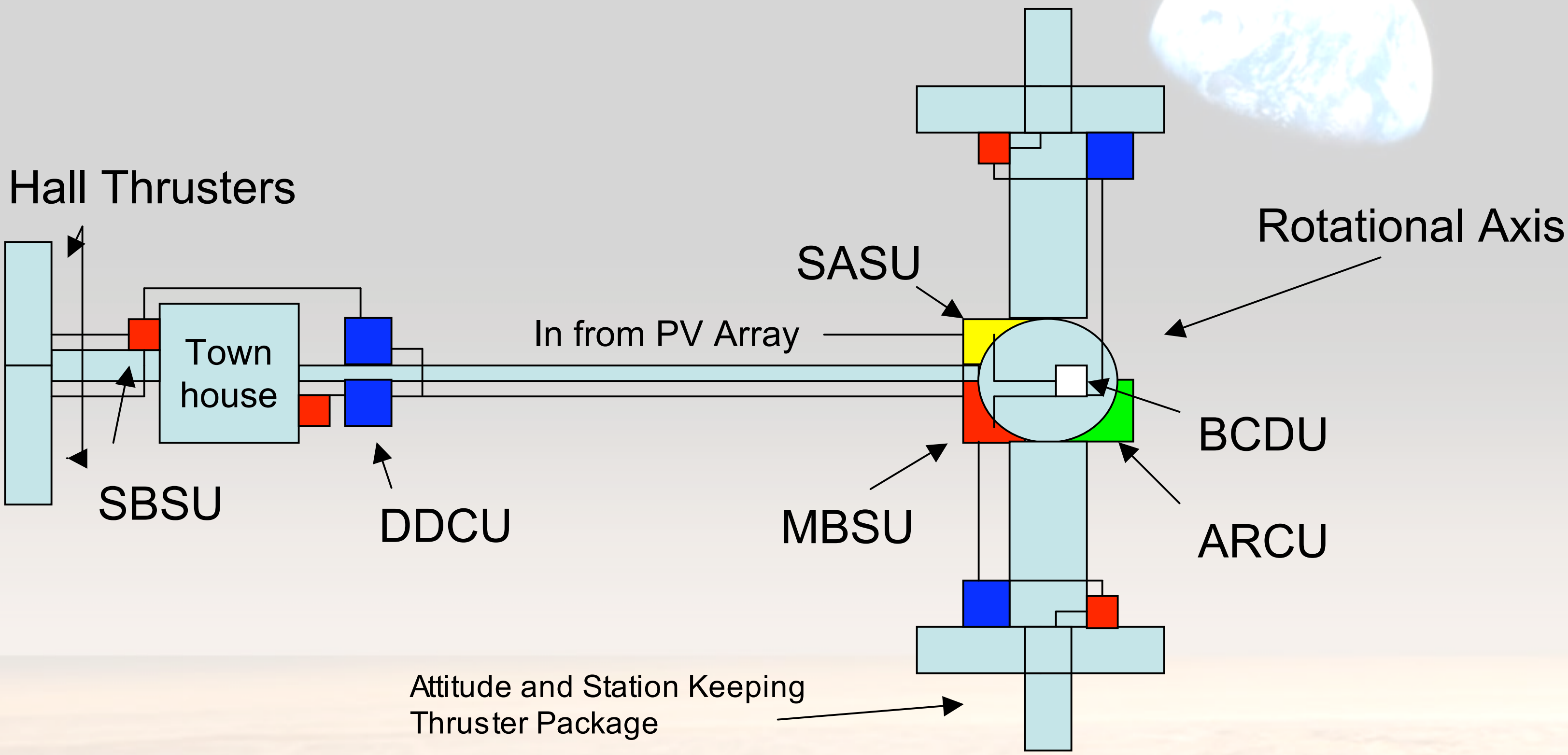
PMAD (cont.)

Mass Analysis

	Quantity	Mass
SASU	1	200 kg
BCDU	1	100 kg
MBSU	1	100 kg
DCSU	5	250 kg
DDCU	3	600 kg
PCU	1	20 kg
Wiring	N/A	1,500 kg
Total		**2,770 kg**

PMAD (cont.)

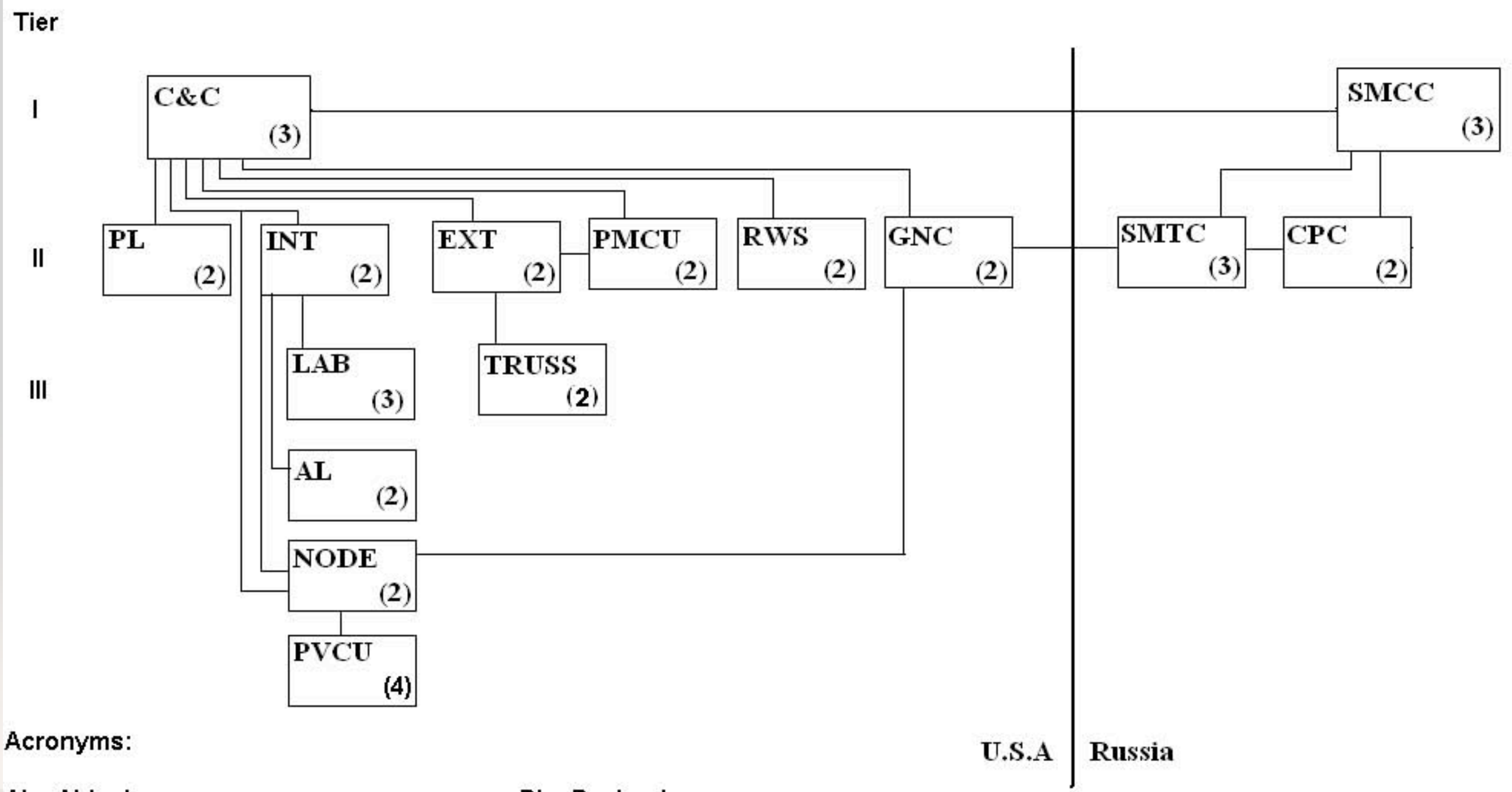
Proposed implementation of the PMAD system



SSP Multiplexer/Demultiplexers (MDMs)

- We will be maintaining the three-tiered architecture that is currently on ISS
- Commands and Telemetry will be sent over a MIL-STD-1553B network
- Most of the MDMs will be reused
- There will be new MDMs added to the truss

SSP MDM Layout



Acronyms:

AL - Airlock
C&C – Command and Control
CPC – Control Post Computer
EXT - External
GNC – Guidance, Navigation and Control
INT - Internal
PL - Payload
PMCU – Power Management Control Unit
PVCU – Photovoltaic Control Unit
RWS – Robotics Workstation
SMCC – Service Module Central Computer
SMTC – Service Module Terminal Computer

MDM Tiers

- Tier 1 (control tier)
  - Send commands to SSP systems
- Tier 2 (local tier)
  - Execute system specific applications
- Tier 3 (user tier)
  - Provide commands and read telemetry from the sensors and effectors

MDM Operation

- For MDM systems that are two-fault tolerant, one MDM will be on as primary, one will be on in a standby mode, and the third will be off
- For MDM, systems that are one-fault tolerant, one MDM will be on, and the other will be off

Truss MDMs

- The two Truss MDMs will be located on the main truss structure
- The purpose of the Truss MDMs is to process the data from the accelerometers mounted on the truss, and the load cells mounted on the cables.

Truss MDM Hardware

- (1) Processor Board (10 W)
- (1) 1553B Board (3.6 W)
- (1) Mass Memory Module (5 W)
- (7) 4-Port Serial I/O Boards (1 W each)
- (1) 130 W heater (to maintain temp of 0 °C while MDM is off)
- The MDM will be housed in a 0.3 m^3 aluminum cube that is coated with epoxy black paint

Accelerometers

- The accelerometers will be used to measure the motions of each truss sections
- There will be two accelerometers mounted on each truss section
- The accelerometers will also be used to monitor the health of the trusses by measuring the change in the vibration signature of the station

Accelerometer Requirements

- Range: ± 1.0g (0.001g resolution)
- Temperature range: -35 to 125 °C
- Operating temperature: 25 °C
- Number of axes: 3
- Housing: 0.05 m^3 cube
- Coating: Epoxy black paint
- Internal power: 6.1 W
- Interface: RS-485

Tension Cable Load Cells

- The tension cable will connected to the townhouses through a load cell.
- Load cell requirements
  - Range: 0 to 4.97 x 10^5 N
  - Temperature Range: -35 to 125 °C
  - Operating Temperature: 25 °C
  - Interface: RS-485
  - Housing: Cylinder (h = 0.0508 m, d = 0.0508 m)
  - Coating: Epoxy Black Paint
  - Internal Power: 4.79 W

Thermal Environment

- Surface temperature varies as Earth moves around the sun and station moves around Earth
- Three sources of heating
  - Sun
  - Earth infrared (IR)
  - Sun reflected by Earth

Thermal Environment

- Worst case cold temperature (SSP crosses into night): 221 K
- Worst case hot temperature (SSP at closest point to the sun): 261 K
- Total surface area of 3,270 m^2
- Using the assumption that the station is an isothermal sphere the absorbing surface area is 818 m^2

Heat Flux

	Hot (kW)	Cold (kW)
Sun	236	0
Sun reflected by Earth	96	0
Earth IR	211	211
Internal power	300	300
Total	843	511
Radiated	688	354
Remaining	155	157

Radiators

- ISS Photovoltaic Radiators and Heat Rejection System Radiators used
- PVR
  - Radiate 11.5 kW
  - 961 kg
  - 3.4 m x 19.6 m
- HRS
  - Radiate 11.8 kW
  - 1,120 kg
  - 3.4 m x 22.9 m

Radiators

- Need to dissipate 159 kW of heat
- 8 PVR radiators
  - 92.0 kW
  - 7,690 kg
- 6 HRS radiators
  - 70.8 kW
  - 6,720 kg
- 165 kW of heat dissipation
- Total radiator mass: 14,400 kg

Placement of Radiators

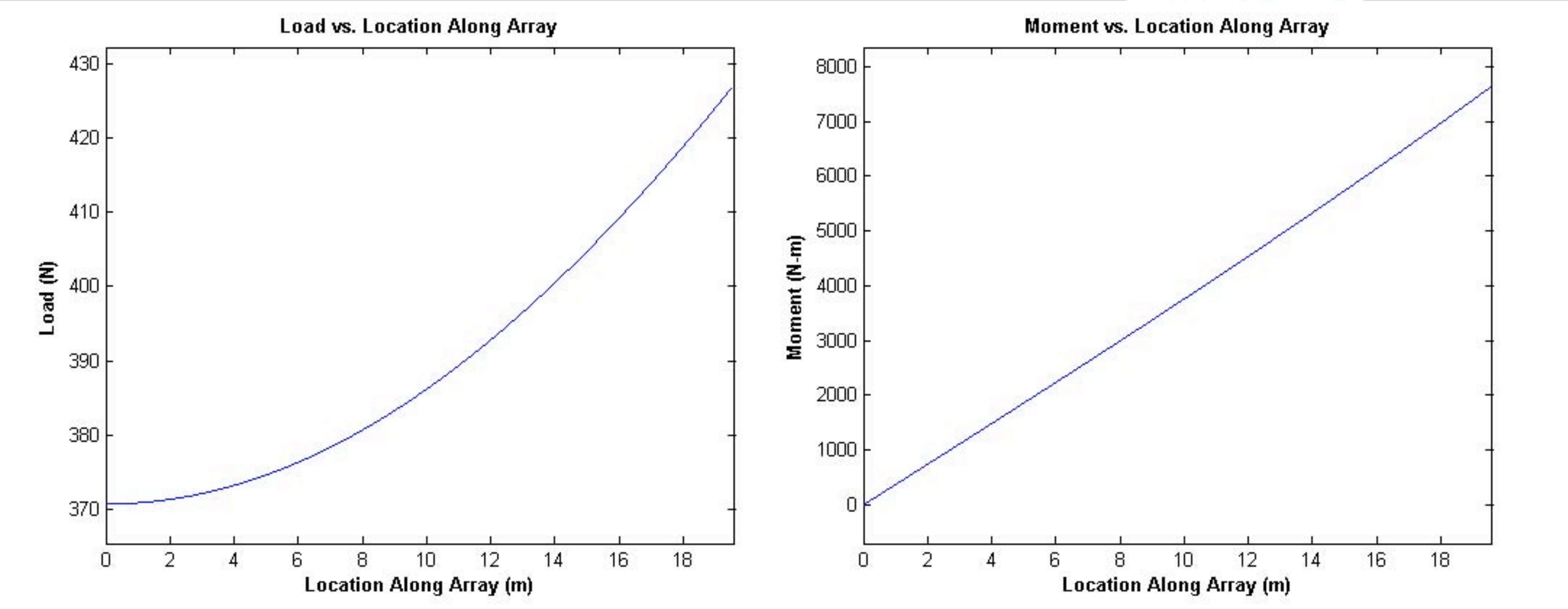
- Place the radiators behind the solar arrays
  - 2 PVR radiators on P6 and S6
  - 2 PVR radiators on P4 and S4
  - 3 HRS radiators on P1 and S1

- Each using the existing radiator mounting points on the ISS trusses

Radiator Support

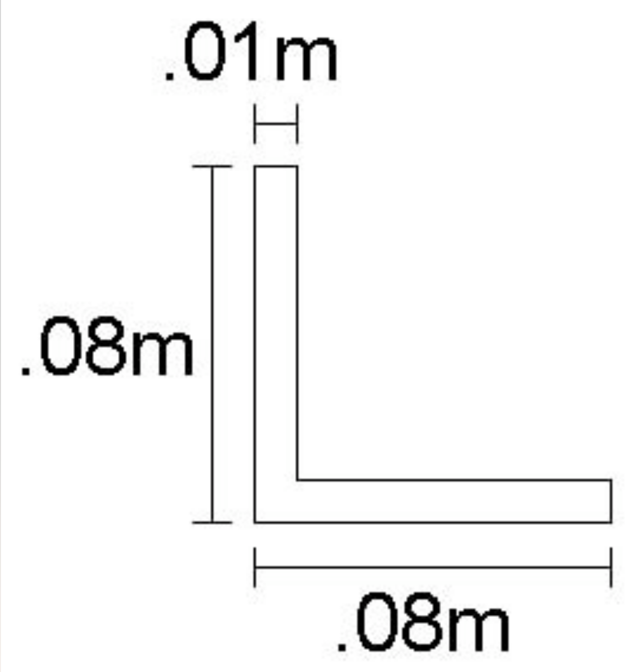
- Radiators mounted on the rotation portion of the station need to be reinforced against bending
- The worst load will occur on the PVR radiators on the S4 and P4 trusses
  - Mount a beam running down the side of the radiators to take the bending load

Radiator Support



Radiator Support

- The maximum stress experienced by the beam will be 1.25×10^8 Pa
- The bar will be made of aluminum with a yield strength of 4.14×10^8 Pa
- SF of 3.3

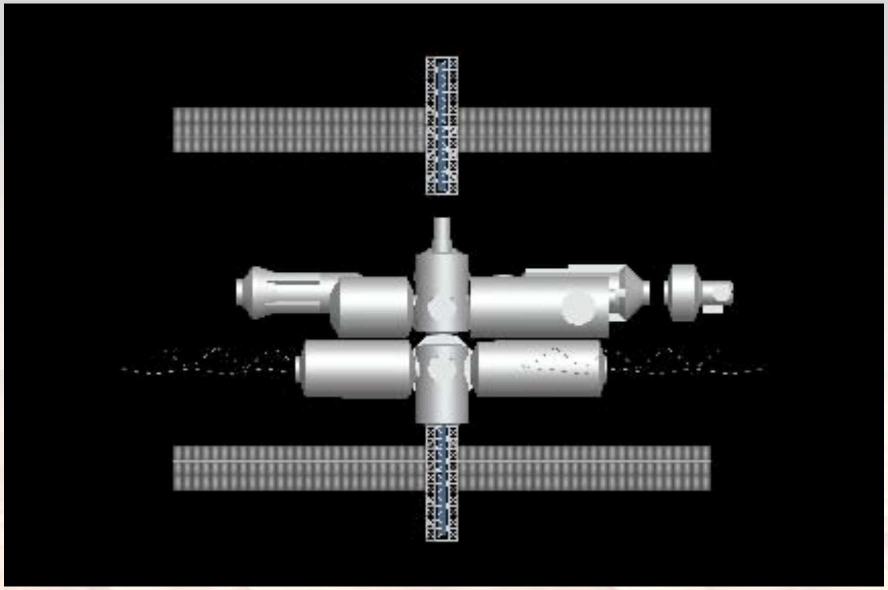


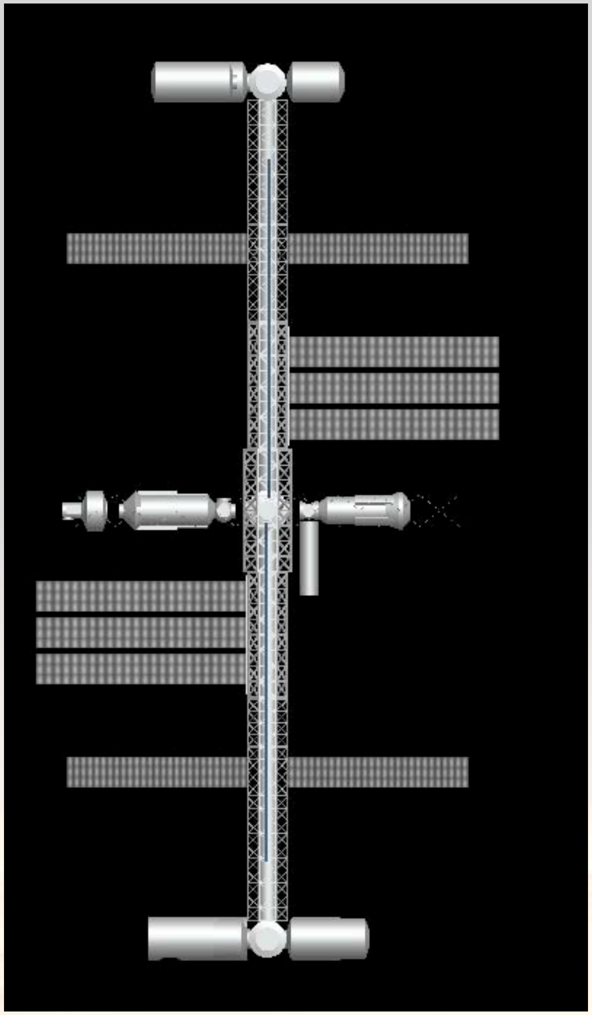
Radiator Support

- Each beam will have a mass of 81 kg
- All 6 HRS radiators and the 4 PVR radiators on P4 and S4 will require reinforcement, total mass of the support structure will be 810 kg

Deployment

- Arrays retracted for launch to fit into launch vehicle payload bay
- On orbit deployed using a scissor mechanism





Surface Coatings

- Once on orbit, the surface coating will decay due to:
  - Atmospheric effects
  - Impacts

Surface	α	ε
Grafoil	0.66	0.34
Vapor-blasted stainless steel	0.60	0.33
Gold/Kapton/Aluminum	0.53	0.42
Epoxy black paint	0.95	0.85
Acrylic Black paint	0.97	0.91
Silicone white paint	0.19	0.88
Silicone white paint after three years	0.39	0.88
Silicate white paint	0.14	0.94
Silicate white paint after three years	0.27	0.94
Kapton (5mil)/aluminium	0.48	0.81
In_2O_3/Kapton/aluminium	0.40	0.71
Quartz fabric/tape	0.19	0.60
FEP(5mil)/silver	0.11	0.80
FEP(2mil)/silver	0.05	0.62

Radiator Gimbaling

- PVR radiators are individually gimbaled, HRS radiators' mounting platform is gimbaled
- All gimbals use a rotary joint with 105° freedom of motion
- When not spinning, can be used to keep radiators parallel to incoming solar rays

Communications – Station to Ground

Requirements

- C/N of 13.5 dB
- Frequency Bandwidth of 58.5 MHz
- Data rate of 44.7 Mbps
  - 14 Mbps HDTV Channel 1
  - 14 Mbps HDTV Channel 2
  - 16.7 Mbps for other uses

Communications – Omnidirectional

- To TDRSS satellites
  - Power required = 33,000 W (not viable)
- To ground
  - Power required = 135 W
  - Interference concerns with other satellites
  - Lack of availability of ground stations
- Backup
  - Power required to TDRSS = 70 W
  - Lower bandwidth (~120 kHz)

Communications – Directional

- To TDRSS (Radio)
  - Power Allocated = 150 W
  - Margin of 6.72 dB
- Laser?
  - Very high data rate (Gbps possible)
  - Small beamwidth
    - Very high pointing accuracy required
    - Limited observation site availability
  - Not designed for constant communications

Communications – Antennas

- Antenna pointing requirements
  - Beamwidth (margin of error) = 2.25°
  - Solar precession = 1°/day
  - TDRSS motion = 0.7-2.25°/min
  - Station instability = 1.8° oscillation every 26 s
  - Expect to re-point once per minute (est.)
- Antenna Gain ~30 dB
- Mass ~100 kg total (conservative est.)
- Limited redundancy: 30° band

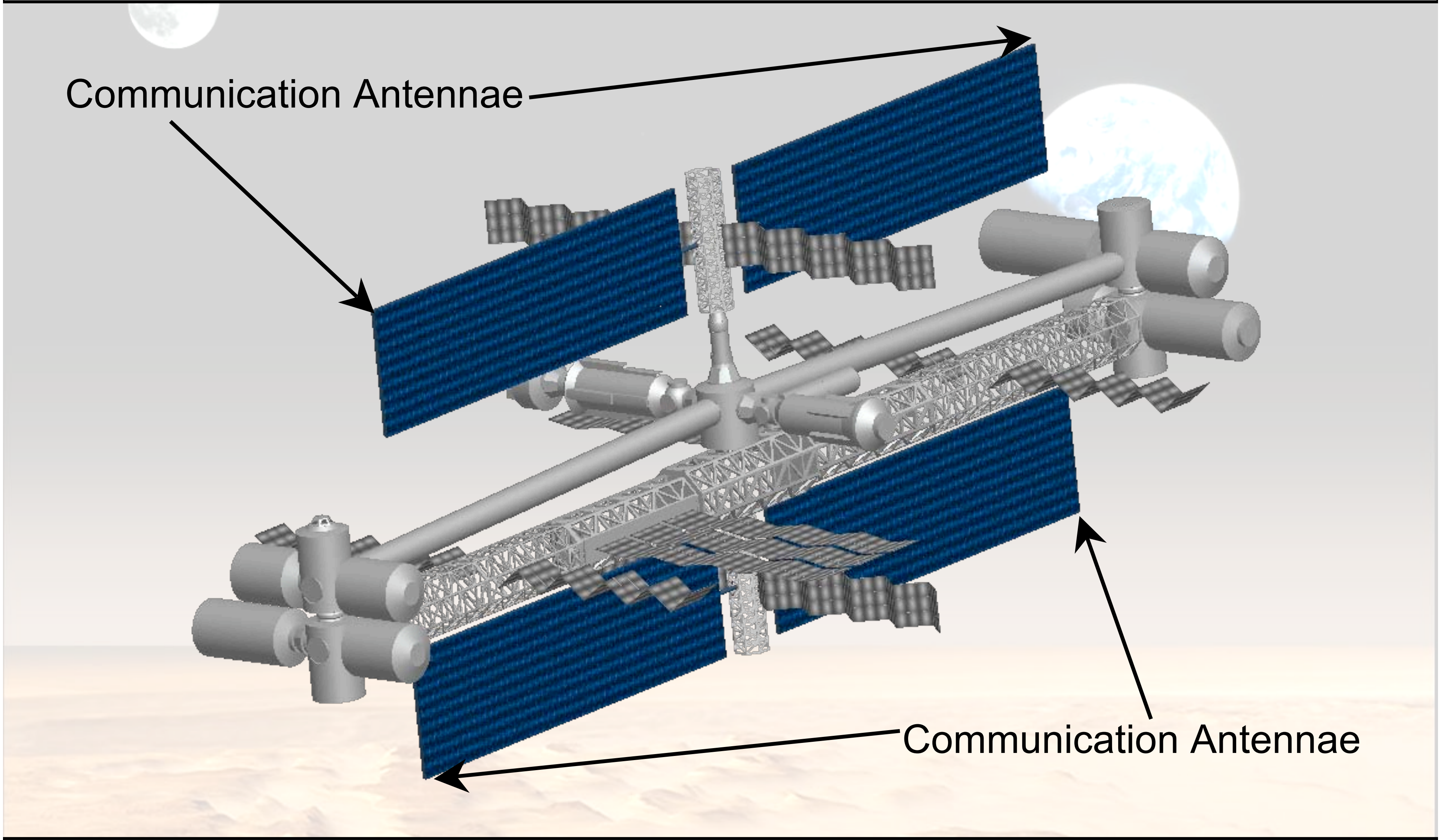
Communications – Overview

- Station-to-ground
- Station-to-spacecraft
- Backup
- Compression system for HDTV
  - Reduces required bandwidth (power) by factor of 100 (1.5 GHz to 14 MHz)
  - Requires only 150 W of power

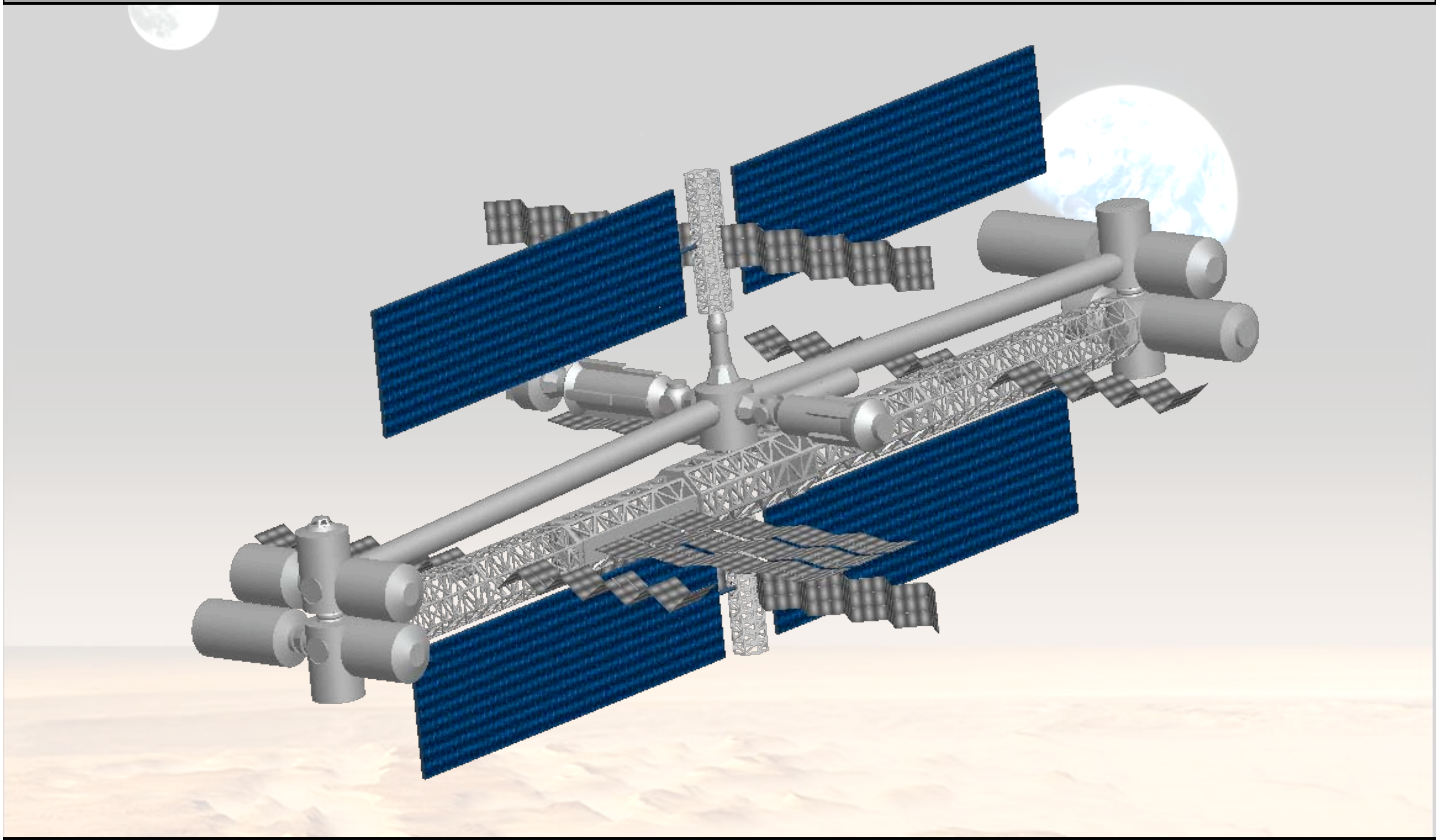
Communications Configuration

- Radio (Ku-band or S-band)
  - Omni-directional antenna
  - Directional antenna
- Laser communication system

Antenna Locations



Intermission



Station Atmosphere

Level 1 Requirement for SSP:

Variable atmosphere: 8.3 to 14.7 psi

- Oxygen will be pressurized to sea level equivalent of 3.1 psi
- Water vapor partial pressure will vary between 0.12 and 0.28 psi
- Carbon dioxide partial pressure will be limited to 0.15 psi

Station Atmosphere (cont.)

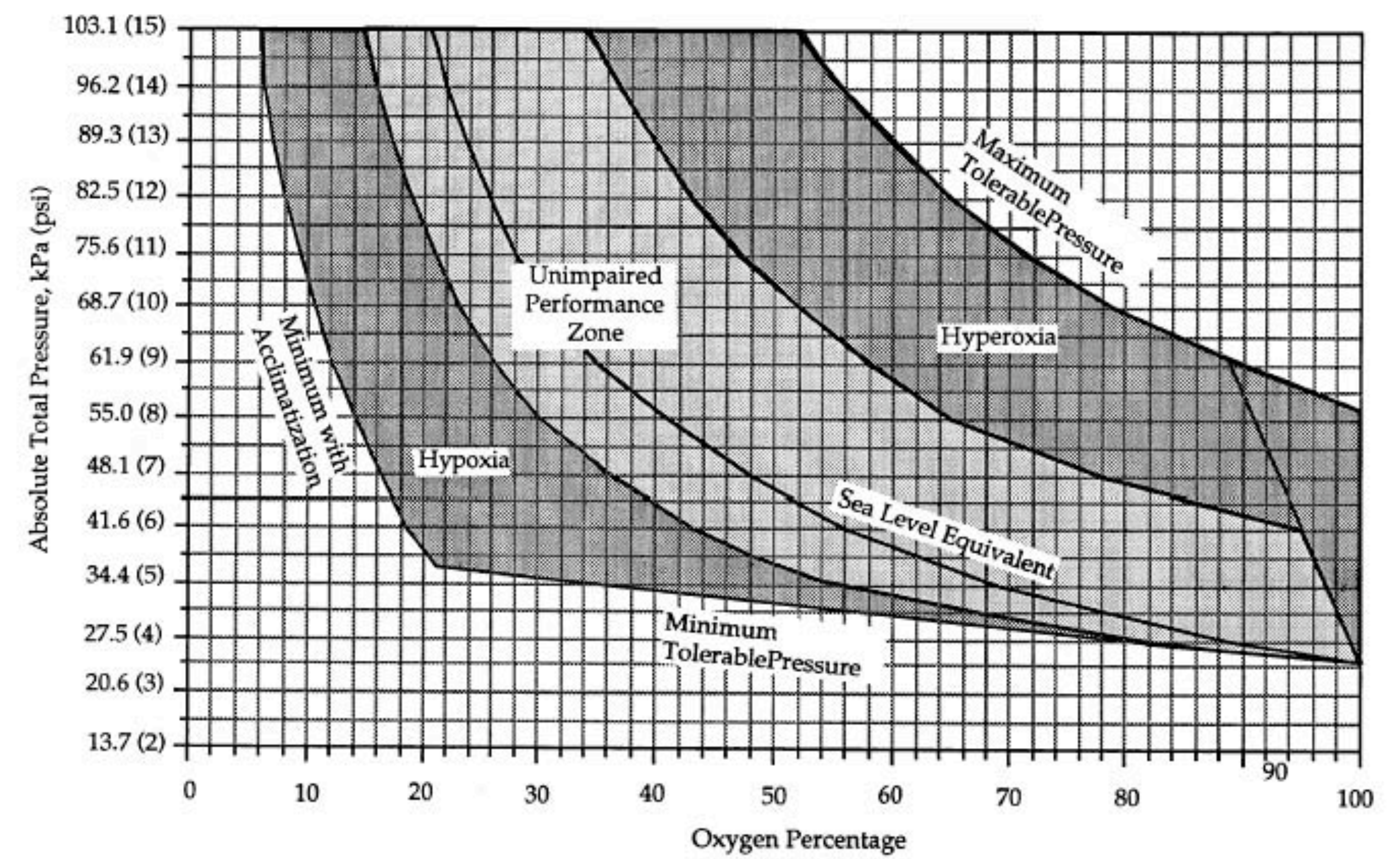


Image: *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems* - "Figure 4. Physiological effects of oxygen concentrations. Note: Extracted from NASA-STD-3000 Vol. 1 Rev. A"

- The graph shows total pressure versus the oxygen percentage
- The areas are darkened that have unreasonable oxygen partial pressures where human performance is impaired

Station Atmosphere (cont.)

Temperature

- Ideal ranges are between 18 °C – 27 °C
- Most comfortable temperatures are between 22 °C – 24 °C
- The station will attempt to operate at 22 °C – 24 °C

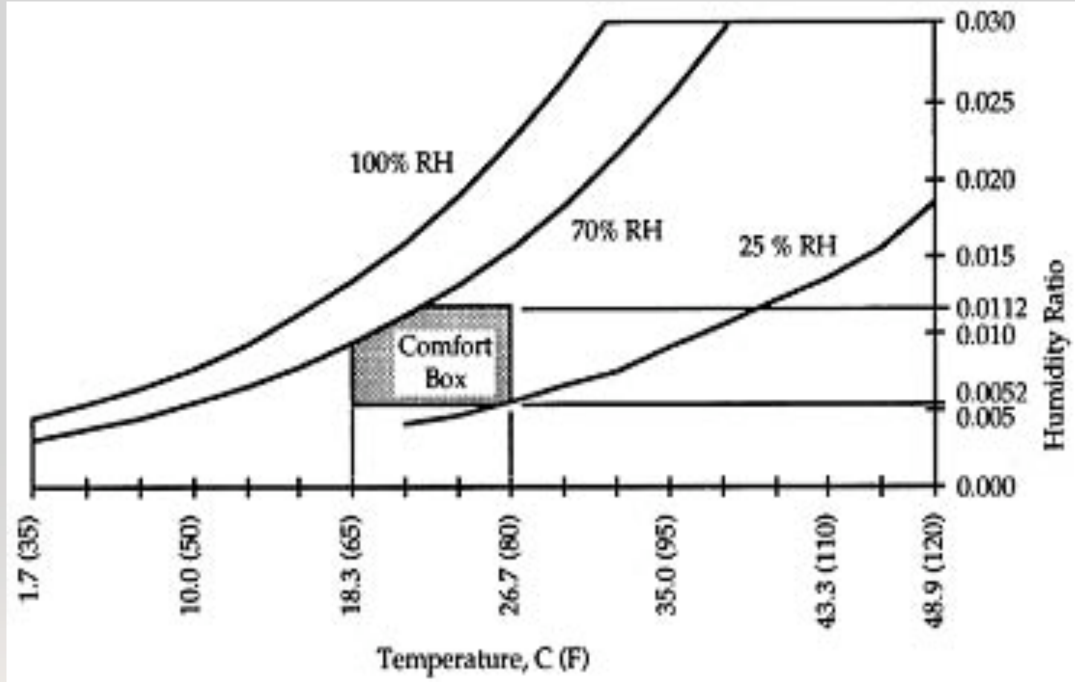


Image: Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems - "Figure 9. Temperature and RH ranges for S.S. Freedom"

Humidity

- The ideal relative humidity range is between 25% and 70%
- SSP will operate within this range

Living Space Requirements

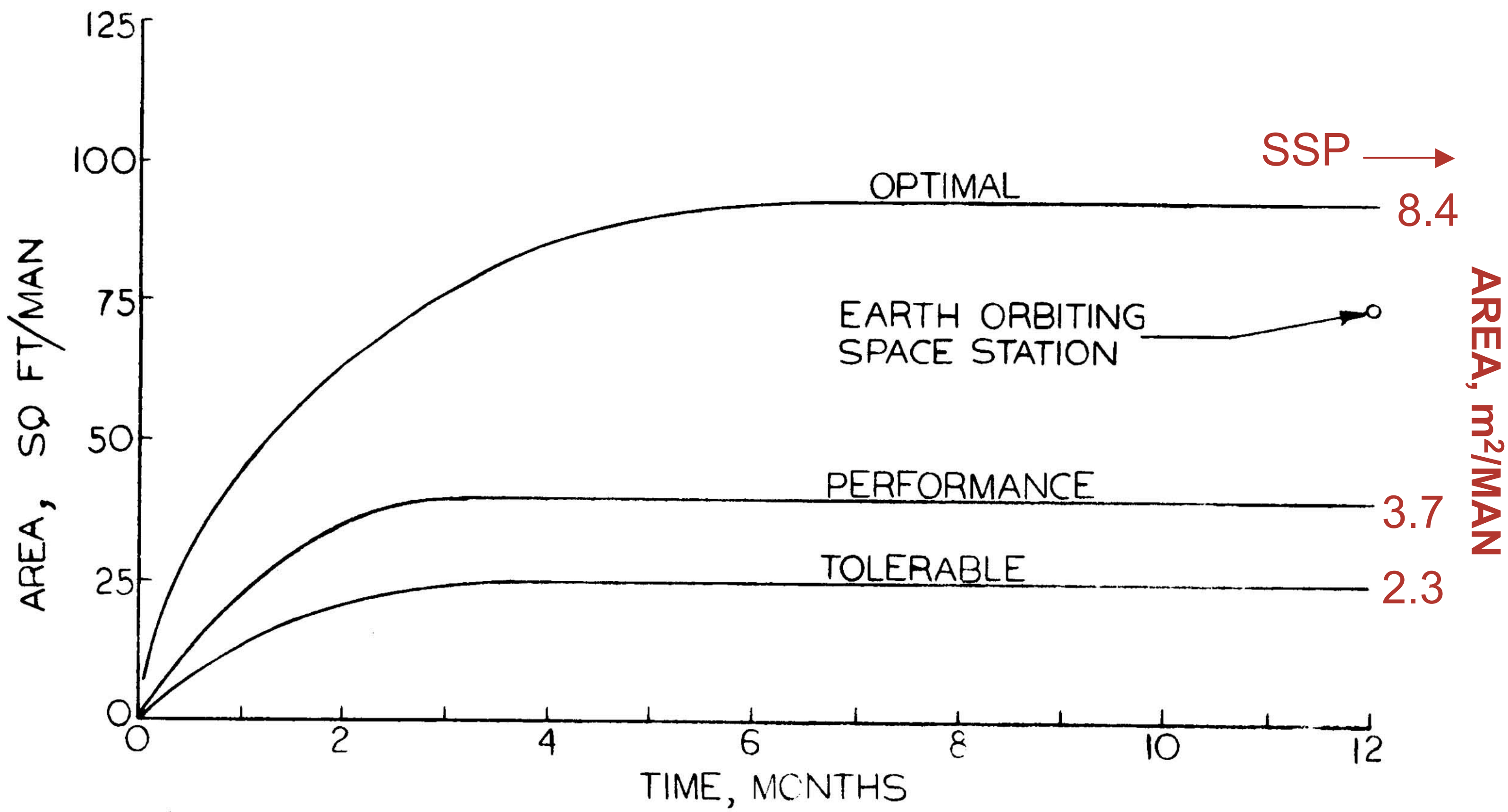


FIGURE 2.2 LIVING SPACE PER MAN (AREA)

Image: Preliminary Technical Data for Earth Orbiting Space Station: Standards and Criteria. Volume II, November 7, 1966.

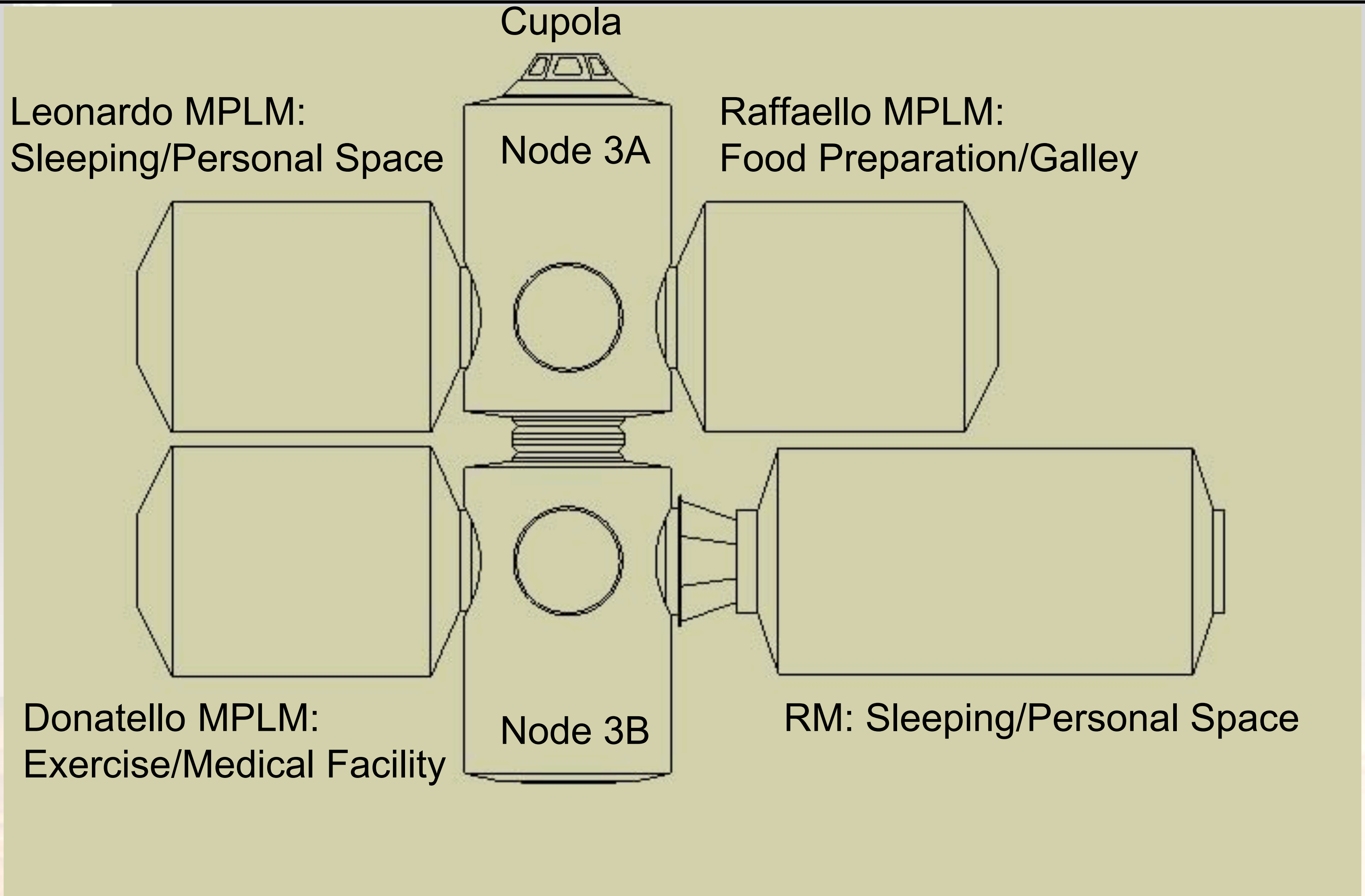
Space Requirement Breakdown

- Private crew quarters: 3.3 m^2/person with 1.4 m^3 of personal storage per crew member
- Wardroom (eating and recreation): 2.0 m^2/person, assuming no more than ⅔ of the crew will occupy it at one time
- Food Preparation Area: 1.5 m^2 – assuming no more than ⅔ of the crew will occupy it at one time
- Exercise Area: 1.4 m^2 – assuming no more than ⅓ of the crew will occupy it at one time

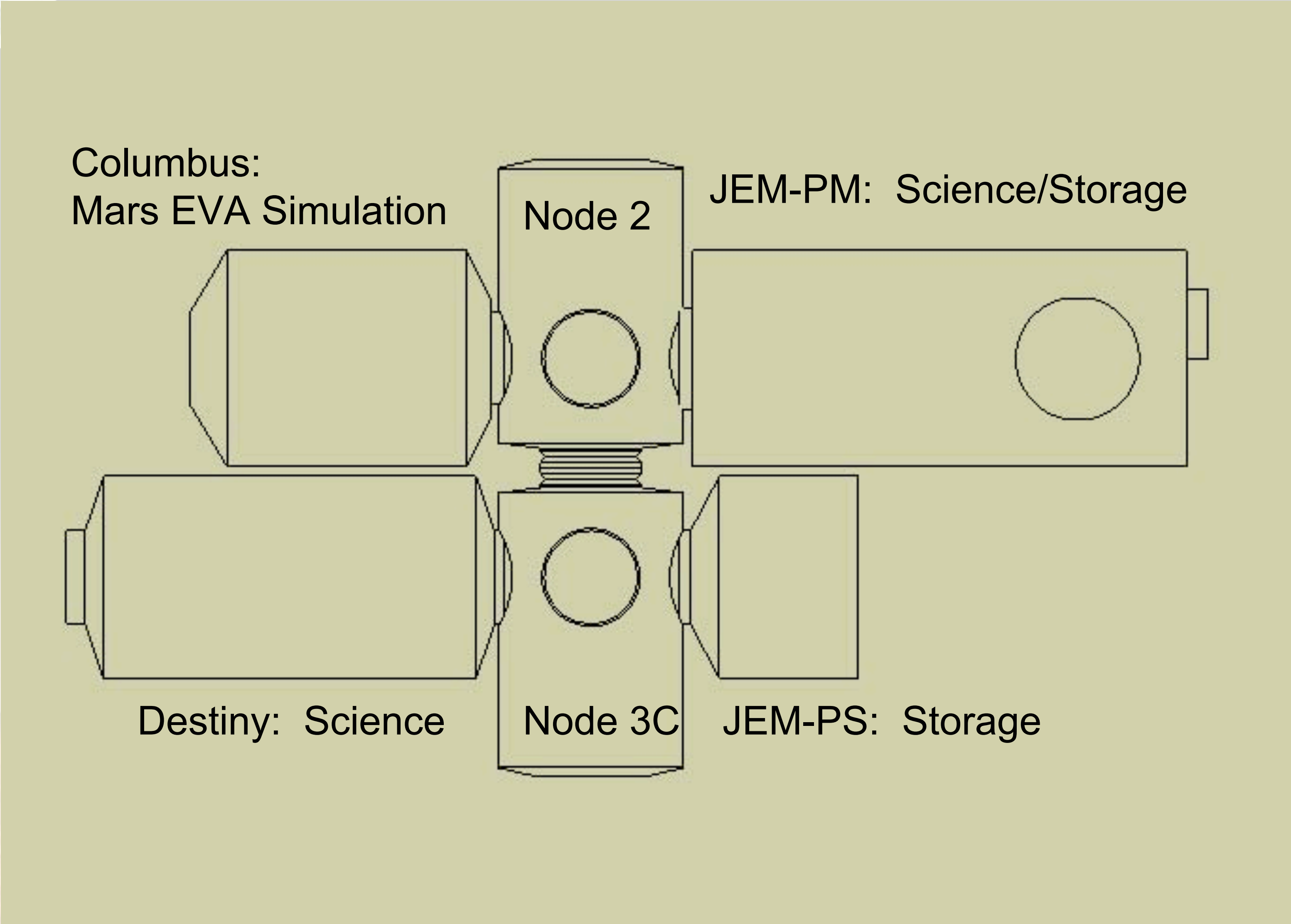
Space Requirement Breakdown (cont.)

- Hygienic Facilities: 1.0 m^2/toilet – need one toilet for every 4 crew members
- Sick Bay: 7.0 m^2 – including private quarters in case illness isolation is required
- Desired minimum ceiling height: 2.76 m based on height of 95th percentile American male and anticipated bouncing associated with reduced gravity

Townhouse A Module Functions



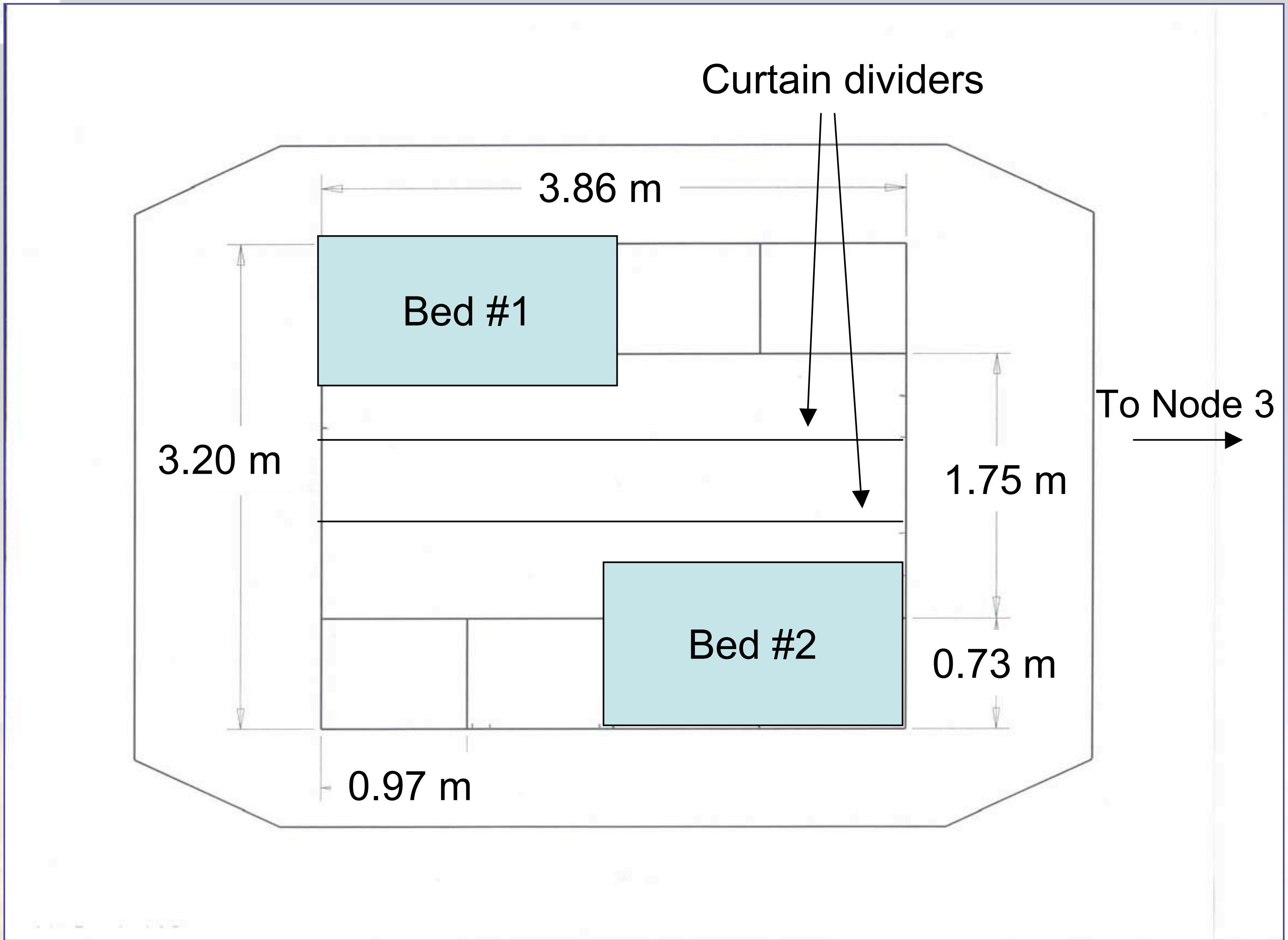
Townhouse B Module Functions



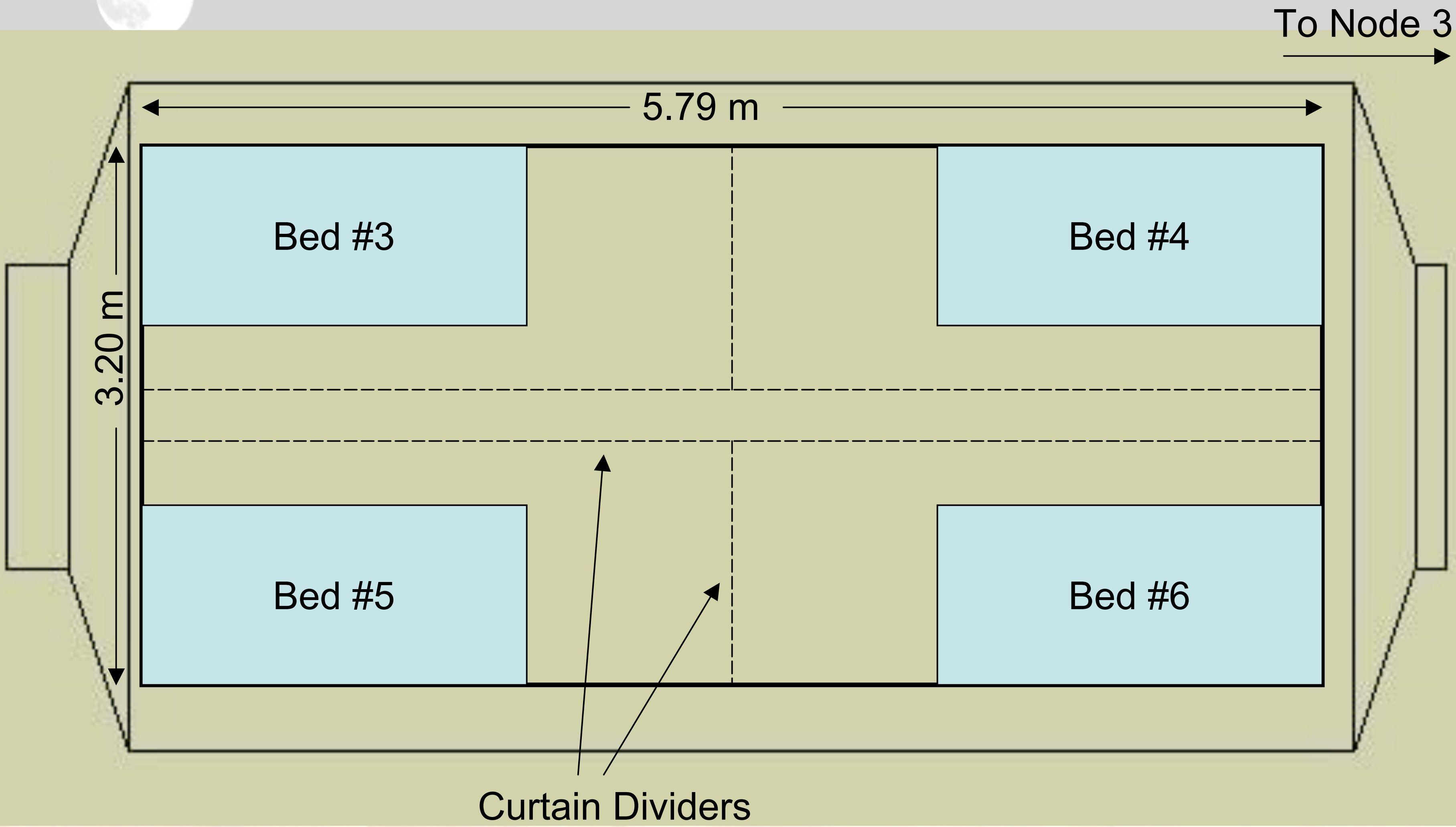
Sleeping Modules

- Each person has at least 3.8 m^2 of floor space
- Removable curtains will separate each of the personal spaces for additional privacy
- Walkway with curtains drawn: 0.55 m wide – accommodates shoulder width of 95th percentile American male
- Each bed is 2 m x 1 m
- Sleeping restraints will be provided for 0g
- Beds lofted – desks and personal storage underneath
- At least 1.4 m^3 of additional personal storage per crew member will be provided under the floor of the RM module

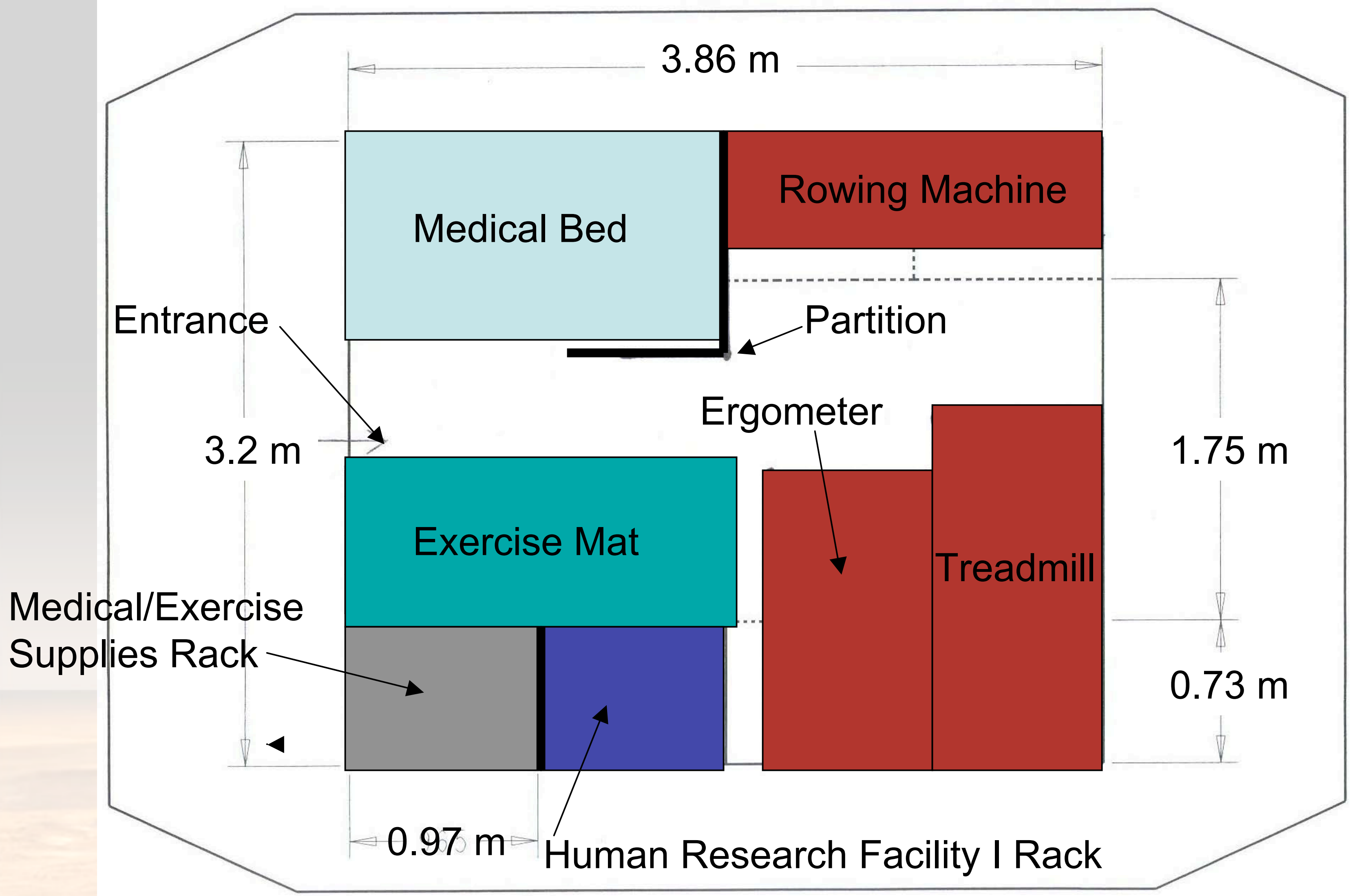
MPLM: Leonardo Floor Plan



Research Module Floor Plan



MPLM: Donatello Floor Plan



Donatello Module

- Exercise Equipment
  - Key to health on long-term stays in zero-gravity
  - Three different exercise machines
- Medical Area and Supplies
  - Medical area to treat minor injuries
  - Supplies for possible health emergencies on orbit
- Human Research Facility I Rack
  - Monitors all aspects of the crew’s health
  - Collect and store experiment data
- Floor Rack Storage Space
  - Racks contain extra medical supplies
  - Cleaning supplies

Exercise Equipment

- Treadmill
  - Helps to retain bone mass in zero gravity
  - Dimensions: 1.8 m x 0.8 m
- Ergometer
  - Cardiovascular workout of lower body
  - Dimensions: 1.5 m x 0.8 m
- Exercise Mat
  - To provide an area for stretching and calisthenics
  - Dimensions: 1.93 m x 0.8 m
- Rowing Machine
  - Cardiovascular workout of upper body
  - Dimensions: 1.9 m x 0.5 m

Medical Supplies

- Medical Rack Storage
  - Antibiotics, disinfections and other pharmaceuticals
  - Blood analyzer, defibrillator and heart rate monitors
  - IV fluids and possibly blood transfusion equipment
  - Ventilators and other first aid equipment
- Medical Bed
  - Area for an astronaut to receive surgery or be treated for other health problems
  - Partially partitioned from exercise area to provide privacy
  - Dimensions: (1 m x 1.9 m)

On-Station Medical Care

- On-station care is important because during an actual Mars mission the astronauts will not have the option of returning to Earth for treatment
- Will be administered by a Crew Medical Officer or an Astronaut Physician treating possible injuries such as:
  - Broken bones, concussions, blood loss, cardiac arrest and decompression sickness
  - Viral or bacterial infections and many other health problems that may develop

Acoustic Environment

- Noise on the station must be kept to a minimum in order to
  - Keep the ability to understand verbal communication with crew members
  - Prevent irritation, maintain the ability to sleep and prevent hearing loss
- U.S. Modules
  - Limit for emissions in a work environment is about 55 dB
  - During sleeping hours its limited to about 45 dB
- Russian Modules
  - Emissions have been recorded about 60 dB although the max is around 74 dB
  - Most of these modules will not be occupied by the crew for long periods of time

Acoustic Environment (cont.)

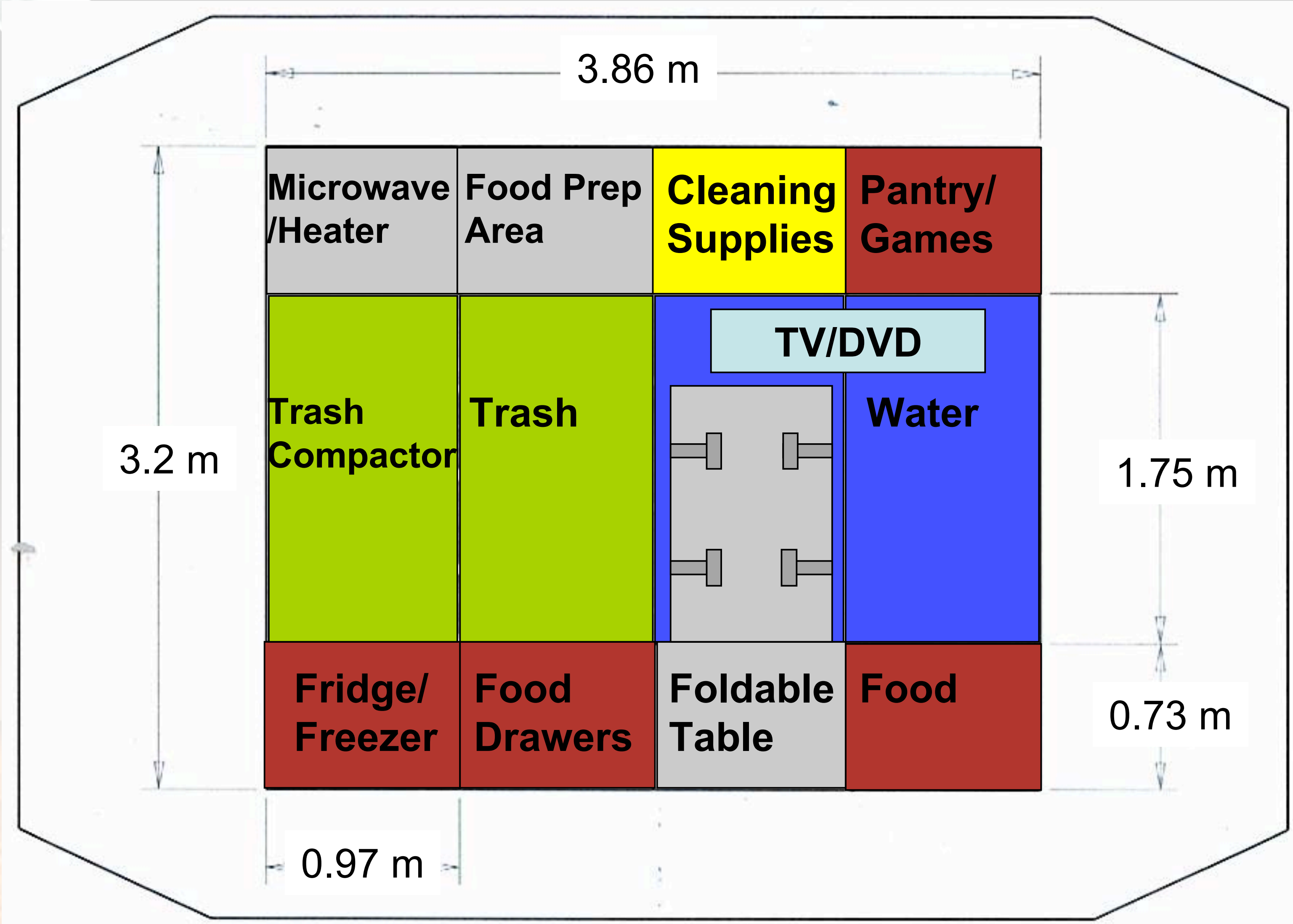
Noise Control

- During periods of exercise in Donatello the hatch of the MPLM may be closed to stop the noise from echoing throughout the station
- If the sleeping quarters are too noisy the astronauts will wear ear protection to damp out low frequency sound
- Extra sound proofing may be required after modifications

Galley Design – Raffaello

- Level 1 Requirements
  - No re-supply
  - Crew of six
  - Gravity between 0g and 1g
  - 5th percentile Japanese female 95th to percentile US male
  - NASA STD-3000
- Overall Galley Characteristics
  - Ceiling height: 2.6 m
  - Floor space: 6.7 m^2
  - All 6 Crew in Galley, 4 of 6 can eat together

MPLM: Raffaello Floor Plan



Station Sanitization

- Bacteria and fungi multiply rapidly in a partial gravity spacecraft environment
- Food preparation, dining, waste management compartments, and sleeping areas will be cleaned and disinfected regularly
- Work areas and living quarters will be cleaned daily with wipes containing antiseptic solutions (total mass and volume of disposable wipes: **1,970 kg or 13.1 m^3**)
- Available cleaning supplies:
  - Biocidal cleanser
  - General-purpose wipes
  - Disposable gloves
  - Vacuum cleaner

Trash Collection

- Utensils/food trays cleaned at hygiene station and re-used
- Soiled clothes, food containers, and other garbage separated into two categories and then discarded:
  - “**Dry**” items
  - “**Wet**” items (can give off unpleasant smells, will be connected to a venting hose)

	Mass	Volume
Trash compactor	150 kg	0.3 m^3
Trash bags	329 kg	6.57 m^3
Vacuum cleaners	13 kg	0.07 m^3

- Trash will be compacted and stored in airtight plastic bags
- Vacuum cleaners (1 primary and 2 spares) will help pick up things and clean the station. They have a hose and extension, several attachments, and a muffler to reduce noise

Storage

- Usable Rack Volume = 1.6 m^3
- Volume and Rack Requirements:

Product	Total Volume (m^3)	Rack Allocation
Food	23	15
Emergency Water	1.8	2
Clothes	10.5	7
Hygienic Supplies	9.86	7
Cleaning Supplies	19.7	13
Solid Waste	18	*Outside JEM-PM*
Trash	1.3	*Outside JEM-PM*

Storage Modules

Townhouse A:

- Donatello (D)
- Raffaello (R)
- Leonardo (L)
- Research Module (RM)
- Node 3A (N3A)
- Node 3C (N3C)

Townhouse B:

- Destiny (Dest)
- Columbus
- JEM PM (PM)
- JEM ELM-PS (PS)
- Node 2 (N2)
- Node 3 (N3B)

Storage Breakdown

Product	Racks	D	R	L	Dest (5)	PM (14)	PS (8)	N3A (8)	N3B (2)	N2 (8)
Food	15	3	-	-	-	8	4	-	-	-
Water	2	2	-	-	-	-	-	-	-	-
Clothes	7	-	-	1	-	6	-	-	-	-
Hygiene	7	-	-	-	2	-	3	-	-	2
Cleaning	13	1	2	-	3	-	1	-	-	6

Note: Waste/trash stored through airlock outside JEM PM until re-supply

Consumables: Food

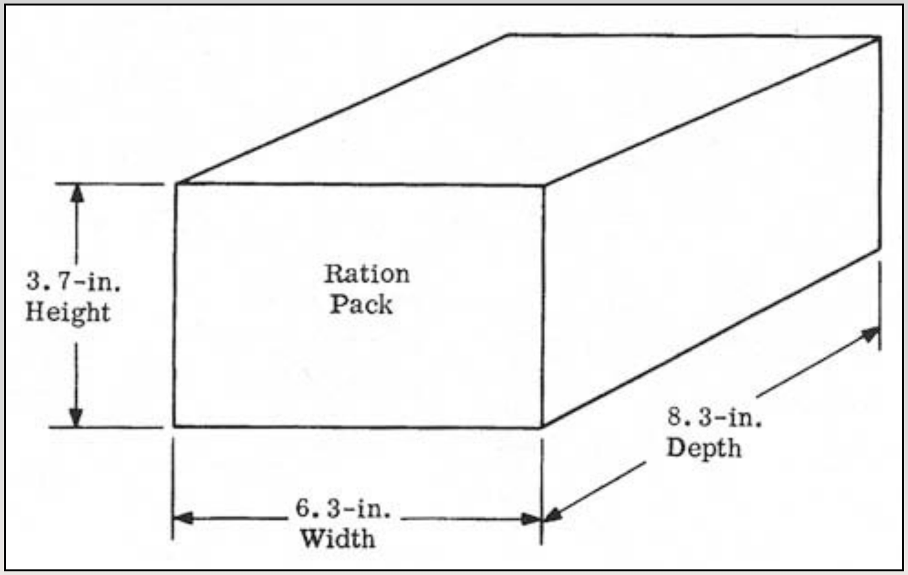
- Daily Food/Water Requirements

Type	Mass Allotted (kg/p-day)
Dry Food	*0.8*
Water from Food	0.9
Drinking Water	0.7
Water – Beverages	1.4
Food Packaging	*0.75*

- 1.55 kg/p-day of food (with packaging)
- Rehydratable, intermediate moisture, natural form foods aboard SSP

Consumables: Food (cont.)

- Astronaut ration pack: 3.2×10^{-3} m^3



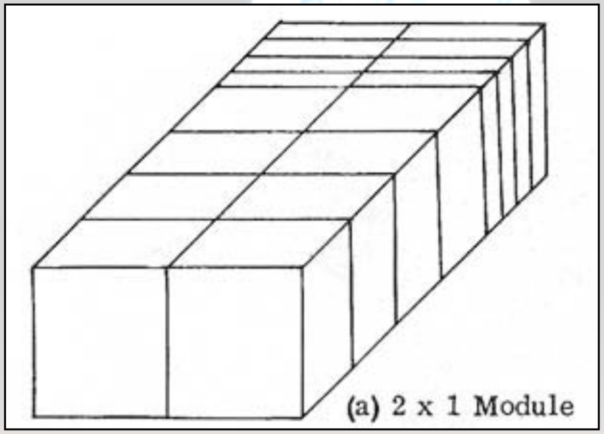


Image: MOL Feeding System

- 16 portions: 4 (rehydratable), 4 (liquid), 8 (bite)
- Varied and flexible menu

Consumables: Food (cont.)

- 6 people • 3 years • 365 days = 6,570 rations
- With 10% Emergency Factor: 7,227 rations
- Total Volume = **23 m^3**

- Dry Food: 0.8 kg/p-day
- Packaging: 0.75 kg/p-day
- 1.55 kg • 7,227 rations = **11,200 kg**

Water Provision

Daily Human Water Needs

Oral Hygiene Water [kg/p-d]	**0.363**
Hand / Face Wash Water [kg/p-d]	**4.08**
Urinal Flush Water [kg/p-d]	**0.494**
Laundry Water [kg/p-d]	**12.5**
Shower Water [kg/p-d]	**2.72**
Dishwashing Water [kg/p-d]	**0**
Drinking Water [kg/p-d]	**2**
TOTAL WATER [kg/p-d]	**22.1**

Water Provision (cont.)

Laundry Water is **56.4% of total water usage**

Oral Hygiene Water [kg/p-d]	0.363
Hand / Face Wash Water [kg/p-d]	4.08
Urinal Flush Water [kg/p-d]	0.494
Laundry Water [kg/p-d]	**12.5**
Shower Water [kg/p-d]	2.72
Dishwashing Water [kg/p-d]	0
Drinking Water [kg/p-d]	2
TOTAL WATER [kg/p-d]	22.1

Water Provision (cont.)

- For a crew of six and a 30-month duration, SSP would need:
  - 121,000 kg of water (with laundry water)
  - 52,900 kg of water (without laundry water – would require disposable clothes)

	Mass	Volume
Disposable Clothes	**2,520 kg**	**8.76 m^3**
Laundry Water	68,300 kg	68.3 m^3
Laundry Water (with reclamation)	10,200 kg	10.2 m^3

Space Station Phoenix will use disposable clothes

- 2.3 kg/p per change of clothes
- 0.008 m^3/p per change of clothes
- Clothes worn for five days

Water Provision (cont.)

Revised Daily Human Water Needs for SSP

Oral Hygiene Water [kg/p-d]	**0.363**
Hand / Face Wash Water [kg/p-d]	**4.08**
Urinal Flush Water [kg/p-d]	**0.494**
Laundry Water [kg/p-d]	**0**
Shower Water [kg/p-d]	**2.72**
Dishwashing Water [kg/p-d]	**0**
Drinking Water [kg/p-d]	**2**
TOTAL WATER [kg/p-d]	**9.63**

Water Reclamation: WRS

Water Recovery System (WRS)

(***Urine Processor Assembly*** and ***Water Processor Assembly***)

• Manufactured by Hamilton Sundstrand
• Produces potable water from cabin humidity condensate, reclaimed urine distillate, used shower water, hand wash and oral hygiene waters, and EVA wastes
• Major components are the *Water Processor Assembly* and *Urine Processor Assembly*
• System is deployed in two dedicated racks located within Node 3A

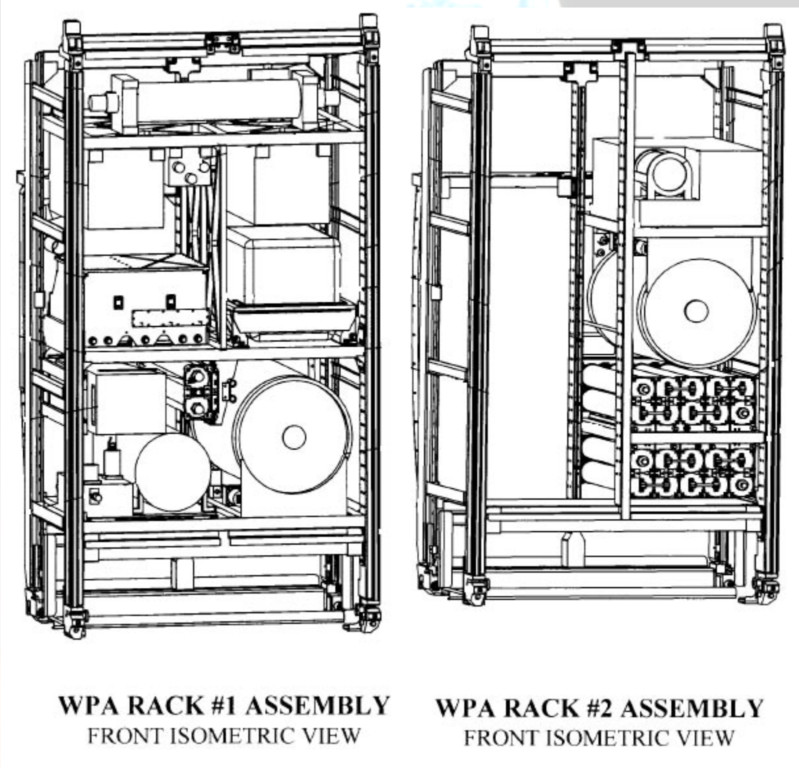
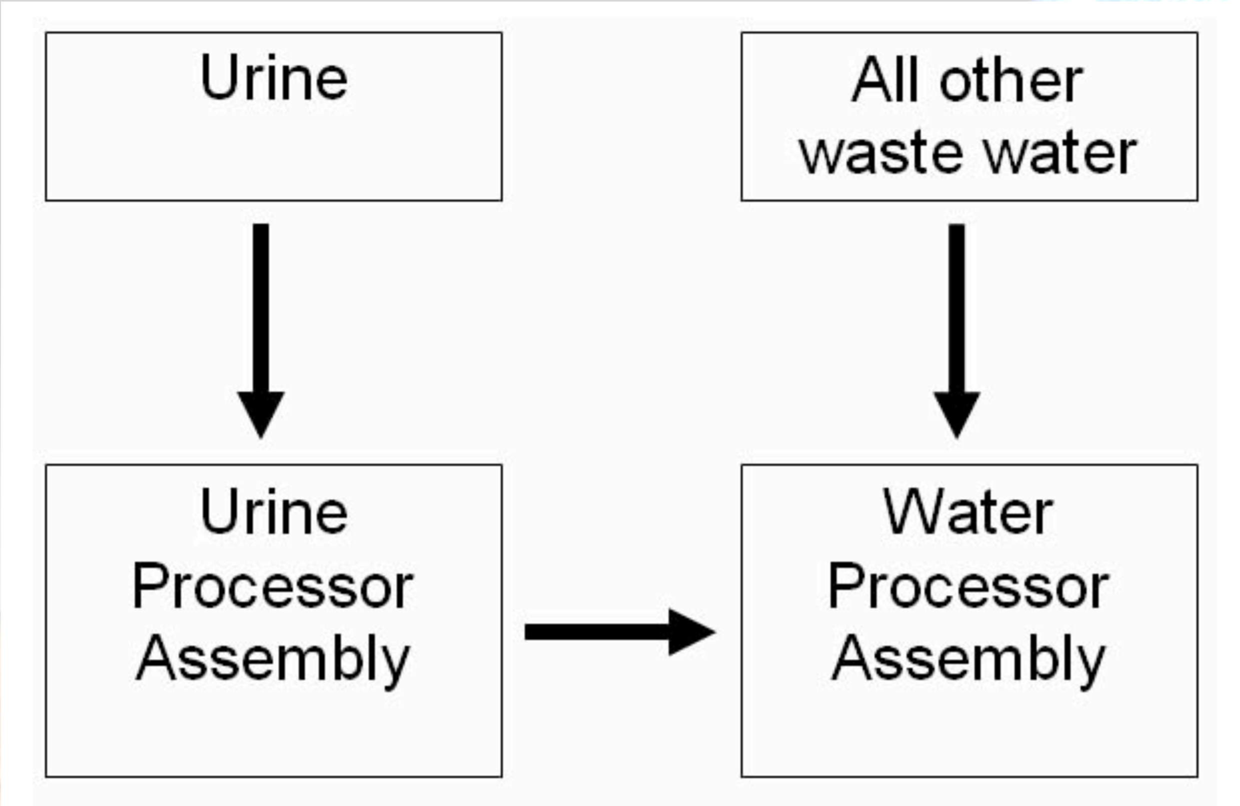


Image: 1991-01-1950 ISS Water Reclamation System Design

Water Reclamation: WRS (cont.)

Water Recovery System (WRS)

(***Urine Processor Assembly*** and ***Water Processor Assembly***)



Water Reclamation: UPA

Water Recovery System (WRS)

(***Urine Processor Assembly*** and ***Water Processor Assembly***)

Urine Processor Assembly (UPA)

- Urine is delivered to the UPA's Wastewater Storage Tank Assembly from the Waste and Hygiene Compartment
- Uses a low-pressure Vapor Compression Distillation process to recover water
  - Boils urine to produce and collect water vapor
  - "Phase change" process - liquid phase to vapor phase to liquid
- Recovered water from urine is then combined with all other wastewaters and sent to the Water Processor Assembly
- Efficiency approximately 85%

Water Reclamation: UPA (cont.)

Water Recovery System (WRS)

(***Urine Processor Assembly*** and ***Water Processor Assembly***)

Urine Processor Assembly (UPA) (cont.)

Flow rate	**8.45 kg/day**
Power	**424 W (processing), 108 W (standby)**
Size	**0.707 m^3**
Weight	**156 kg**

Water Reclamation: WPA

Water Recovery System (WRS)

(*Urine Processor Assembly* and ***Water Processor Assembly***)

Water Processor Assembly (WPA)

- Uses "multifiltration" approach: filtration → ion exchange → carbon filtration → catalytic oxidation
- Free gas and solid materials (hair, lint, etc) removed by a particulate filter before water is processed through a series of multifiltration beds
- Leftover organic contaminants and microorganisms removed by a high-temperature catalytic reactor assembly
- Purity of water checked by electrical conductivity sensors. Unacceptable water reprocessed. Clean water sent back to storage tank
- Efficiency near 100%

Water Reclamation: WPA (cont.)

Water Recovery System (WRS)

(*Urine Processor Assembly* and ***Water Processor Assembly***)

Water Processor Assembly (WPA) (cont.)

Flow rate	**227 kg/hour (delivery)**
Power	**915 W**
Size	**2.12 m^3**
Weight	**658 kg**

Water Provision (cont.)

Water needed for SSP *without* a recovery system:

Construction (3 people, 6 months)	**Gravity Test** (6 people, 10 months)	**Mars Simulation** (6 people, 30 months)
5,290 kg	17,600 kg	52,900 kg

TOTAL: **75,800 kg**

Water needed using the *Water Recovery System* by Hamilton Sundstrand (85% recovery rate):

Construction (3 people, 6 months)	**Gravity Test** (6 people, 10 months)	**Mars Simulation** (6 people, 30 months)
793 kg	2,650 kg	7,930 kg

TOTAL: **11,400 kg**

Emergency Water Sources

- <u>Primary Backup</u>: each townhouse will have its own independent *Water Recovery System*
- <u>Secondary Backup</u>: *Contingency Water Containers* (CWC)
  - "Duffel bags"
  - 40.8 kg each
  - 28-day supply required for emergency situations
  - No water recycling available in emergency situations
  - Total needed: **40 contingency water containers**

Image: http://spaceflight.nasa.gov/living/factsheets/water2.html

Water System Maintenance

- The Water Processor Assembly is a multistage system that uses filters to remove particulate matter and salts
- Filters and other expendables will be replaced periodically as follows:

Pump/Mostly Liquid Separator	720 days
Mostly Liquid Separator Filter	120 days
Particulate Filter	40 days
Multifiltration Bed #1	66 days
Multifiltration Bed #2	66 days
Gas Separator	360 days
Microbial Check Valve	360 days
Ion Exchange	60 days

- Old filters will be discarded

Waste Management System

Hamilton Sundstrand Waste Collection System (WCS)

- Total of 3 WCS
- Located in each Node 3
- Functions at all gravity levels from 0 – 1g
- Separate urine and feces collection systems
- Solids compacted – allows for 20 compactions of 0.11 kg each before the canister must be changed
- Maximum of 1.3 m^3 (1,340 kg) of solid waste will be generated
- Waste contingency bags will be provided in case of failure

Image:http://www.snds.com/ssi/ssi/Applications/SpaceHabitat/WCS.html

Hygiene

- Total of 3 hygienic facilities
- Located in each Node 3
- A “comfort” hygienic set provided to each crew member – contains personal hygienic supplies
- Consumable hygienic products developed to be used with a minimal amount of water
- Wet towels will be used instead of a traditional shower
  - Reduces water consumption
  - Astronauts have preferred this method in reduced gravity conditions
  - No laundry located on station

Image: http://liftoff.msfc.nasa.gov/Shared/News2001/StationPlumbing/HygieneCenter-large

Cabin Atmosphere Parameters

Major Atm. Composition	79% N_2, 21% O_2
Cabin Pressure	8.3 to 14.7 psi
Temperature Range	18.0 ºC to 24.0 ºC
Relative Humidity	25% to 70%
Airborne Particulates	3.5×10^6 max counts/m^3
Ventilation	0.07 m/s to 0.20 m/s

Cabin Atmosphere Control System

Fundamental Systems

1. Atmosphere Control and Supply (ACS)
2. Atmosphere Revitalization (AR)
3. Temperature and Humidity Control (THC)

1. Atmosphere Control and Supply

- Establishes cabin pressurization by introducing N_2 and O_2 at the desired partial pressures (pp)
- Subsystem monitors the total cabin atmospheric pressure and ppO_2/ppN_2
- Relieves cabin over-pressure
- Equalizes pressure between modules
- Detects/recovers from decompression
- Detects hazardous atmosphere

1. ACS: Nitrogen

- N_2 is used as an inert gas to pressurize the cabin
- Acts as a retardant in case of cabin fire
- 0.5% of cabin N_2 lost daily to leakage and airlock purges

SSP Cabin Volume	2,000 m^3
Amount of Nitrogen Required to Pressurize Cabin (14.7 psi, 20 ºC)	1,850 kg
Daily Loss of N_2	9.48 kg

1. ACS: Nitrogen Sources Study

Storage Source	TRL	Tank Penalty (kg/kg N_2)	Yield (kg N_2/kg)	3 Year Mission Mass (kg)*
Cryogenic [1]	9	0.7	1.00	30,600
Gaseous	9	2.0	1.00	47,500
Hydrazine (N_2H_4)	3	0.2	0.88	19,700

*Includes:

- tank mass
- 0.5% leakage loss per day
- 1.15 safety factor and 28 day emergency supply

[1] Includes cryogenic boil off of 0.5% a day

1. ACS: Nitrogen Source : N_2H_4

- Disassociation Process

  $3N_2H_4 \rightarrow 3N_2 + 6H_2$ + heat (exothermic)

- Five system process
  1. Catalytic hydrazine decomposition reactor
  2. Hydrogen separator (removes N_2 at 247 psi and 1,007 K)
  3. Catalytic oxidizer (removes any trace H_2 , NH_3)
  4. Pure N_2 stored in U.S. Airlock ORU N_2 tank
  5. H_2 sent to other subsystems for use

- Two independent process units to be located on external N_2H_4 tank to for heat dissipation

  55 kg each (ESA/ESTEC, 2004 estimate)

1. ACS: Nitrogen Source: N_2H_4

- Proposed: ISS use / ESA future use
- Pros
  - Liquid density comparable to H_2O (1 g/cm^3)
  - Yields H_2 (for other subsystems)
- Con
  - N_2 extracted from process must be absolutely pure of hydrogen to avoid lethal trace amount cabin contamination

SSP Hydrazine Mission Requirement

	Construction	Gravity Test	Mars Sim.
Crew Members	3	6	6
Stay Duration	180 days	300 days	900 days
ATMOSPHERE PRESSURIZATION N_2H_4 REQUIREMENT			
N_2 Leakage	1,950 kg	3,250 kg	9,750 kg
28 Day Emergency	304 kg	304 kg	304 kg
Safety Factor	1.15	1.15	1.15
TOTAL N_2H_4	**2,591 kg**	**4,085 kg**	**11,560 kg**

1. ACS: Oxygen

Needed to meet crew metabolic requirements and establish cabin atmosphere:

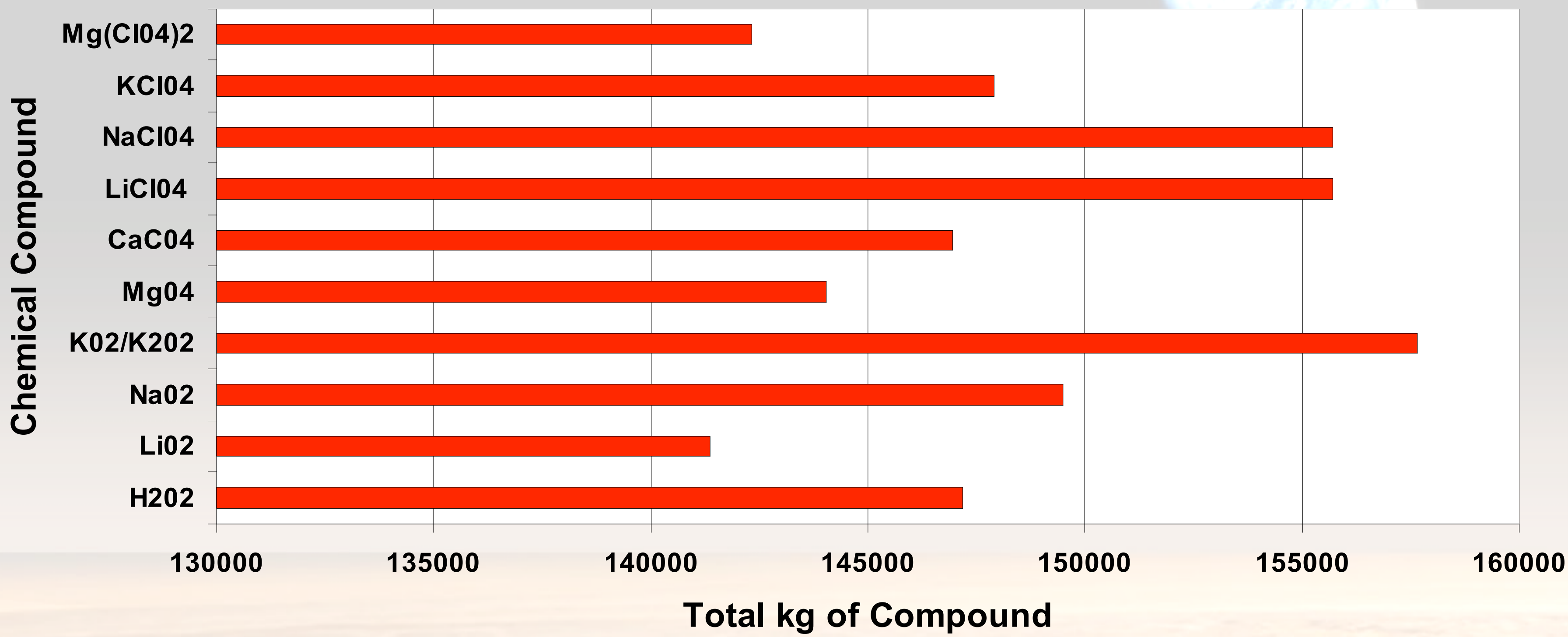
Crew Metabolic Requirement (6X)	0.85 kg O_2/person-day
Experiments	0.12 kg O_2/day
Rats (72)	1.08 kg O_2/day
Cabin Leakage	2.67 kg O_2/day
Total for O_2 Required	**8.97 kg O_2/day**

SSP Cabin Volume	2,000 m^3
Max Amount of Oxygen Required to Pressurize Cabin (8.3 psi, 20 ºC)	580 kg

1. ACS: Oxygen Sources

Non–Regenerable O_2 Chemical Compounds

Compound Masses for a 3 Year Mission



CONCLUSION: Unreasonably large mass, too expensive to launch

1. ACS: Oxygen Sources

Storage Source	TRL	Tank Penalty (kg/kg O_2)	Yield (kg O_2/kg)	3 Year Mission Mass (kg)*
Cryogenic [(1)]	9	0.7	1.00	29,900
Gaseous	9	2.0	1.00	52,600

*Includes:
- tank mass
- 0.5% leakage loss per day
- 1.15 safety factor and 28 day emergency supply

[(1)] Includes cryogenic boil off of 0.5% a day

CONCLUSION: Large masses involved are expensive to launch

1. ACS: Regenerable O_2 Sources

	TRL Apr-05	SubSystem Mass (kg)	SubSystem Vol (m^3)	SS Rack Mass (kg)	Power (kW)	Heat (kW)	On ISS ?
Regenerable 0_2 Sources							
Static Feed Water Electrolysis (SFWE)	4	54	0.03	-	0.96	?	No
Solid Polymer Water Electrolysis (SPWE)	9	64	0.05	680	0.32	?	Yes
Water Vapor Electrolysis	4	?	?	-	?	?	No
CO_2 Electrolysis	4	?	?	-	?	?	No

1. ACS: SPWE O_2 Generation

$$2H_2O + \text{Energy} \rightarrow 2H_2 + O_2 + \text{Heat}$$

- Water electrolyzed using a solid polymer electrolyte membrane
- Product hydrogen to be used by CO_2 removal
- Mature technology, used on MIR and the ISS

Production Need	8.97 kg-O_2/day
H_2O Required	10.08 kg-H_2O/day

1. ACS: Pressure Control Assembly

- Regulates cabin atmospheric pressure by introducing and maintaining proper partial pressures of N_2 and O_2
- Monitors cabin pressure sensors
- Located on Node 3 of each townhouse
- Responsible for detecting pressure imbalance in the cabin or depressurization

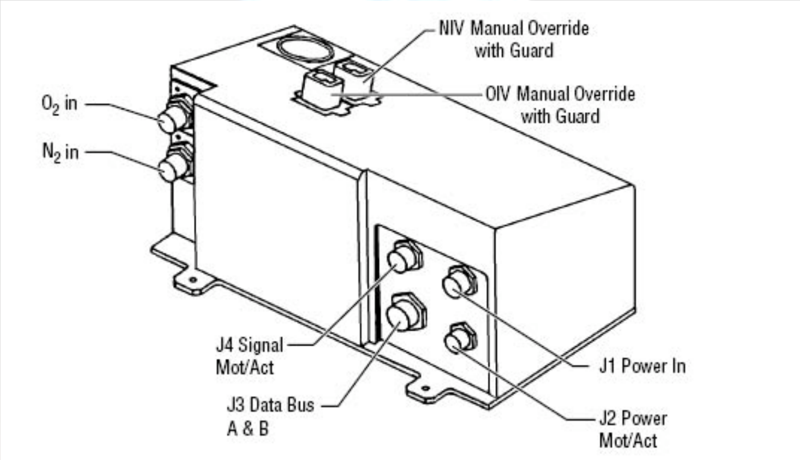


Image: "PCA", NASA/TM-1998-206956/VOL1

Component	Units	Mass (kg)	Vol. (m^3)	Power (kW)
PCA	2	11.2	0.04	0.12
Pressure Sensors	27	0.30	-	-

2. Atmosphere Revitalization (AR)

- CO_2 monitoring, removal, reduction
- Monitoring of atmospheric constituents
- Trace contaminant removal and disposal
- All AR subsystems located on AR Rack

2. AR: Carbon Dioxide Production

Carbon dioxide must be removed from the atmosphere and concentrated to prevent it from reaching *toxic* levels ($ppCO_2$ < 0.15 psi)

Human Metabolic Production (6X):	1.00 kg CO_2-p/day
Total Animal (the mice) Production:	0.14 kg CO_2/day
Total CO_2 to be removed:	**6.14 kg CO_2/day**

2. AR: CO_2 Removal Systems

First we need to remove the CO_2 from the cabin atmosphere

	TRL Apr-05	SubSystem Mass (kg)	SubSystem Vol (m^3)	SS Rack Mass (kg)	Power (kW)	Heat (kW)	On ISS ?
CO_2 Removal Systems							
2-Bed Molecular Sieve (2BMS)	9	48	0.09	-	0.23	?	No
4-Bed Molecular Sieve (4BMS)	9	88	0.11	-	0.54	?	Yes
Solid Amine Water Desorption (SAWD)	4	55	0.04	-	0.57	?	No
Electrochemical Depolarization Concentration	4	42	0.06	-	0.04	0.34	No

2. AR: SSP CO_2 Removal System

Electrochemical Depolarized Concentrator

$$2CO_2 + 2H_2 + O_2 \rightarrow 2H_2O + \mathbf{2CO_2} + \text{DC power} + \text{heat}$$

- Uses electrolyte matrix, anode, and cathode to *concentrate* CO_2
- Can process 2,610 kg/day of cabin atmosphere
- Can concentrate up to 6-8 kg CO_2 per day
- THC system must dissipate EDC heat
- 0.03% of O_2 that passes through is consumed

2. AR: CO_2 Reduction System

Second, we need to reduce the concentrated CO_2 from the removal system into something we can use

	TRL Apr-05	SubSystem Mass (kg)	SubSystem Vol (m^3)	SS Rack Mass (kg)	Power (kW)	Heat (kW)	On ISS ?
CO_2 Reduction Systems							
Bosch	4	68	0.09	1840 (est.)	0.24	0.31	No
Sabatier	6	31	0.01	500 (est.)	0.13	0.27	JSC Testing
Advanced Carbon-Formation Removal System	4	108	0.3	107.6	0.3	0.15	No

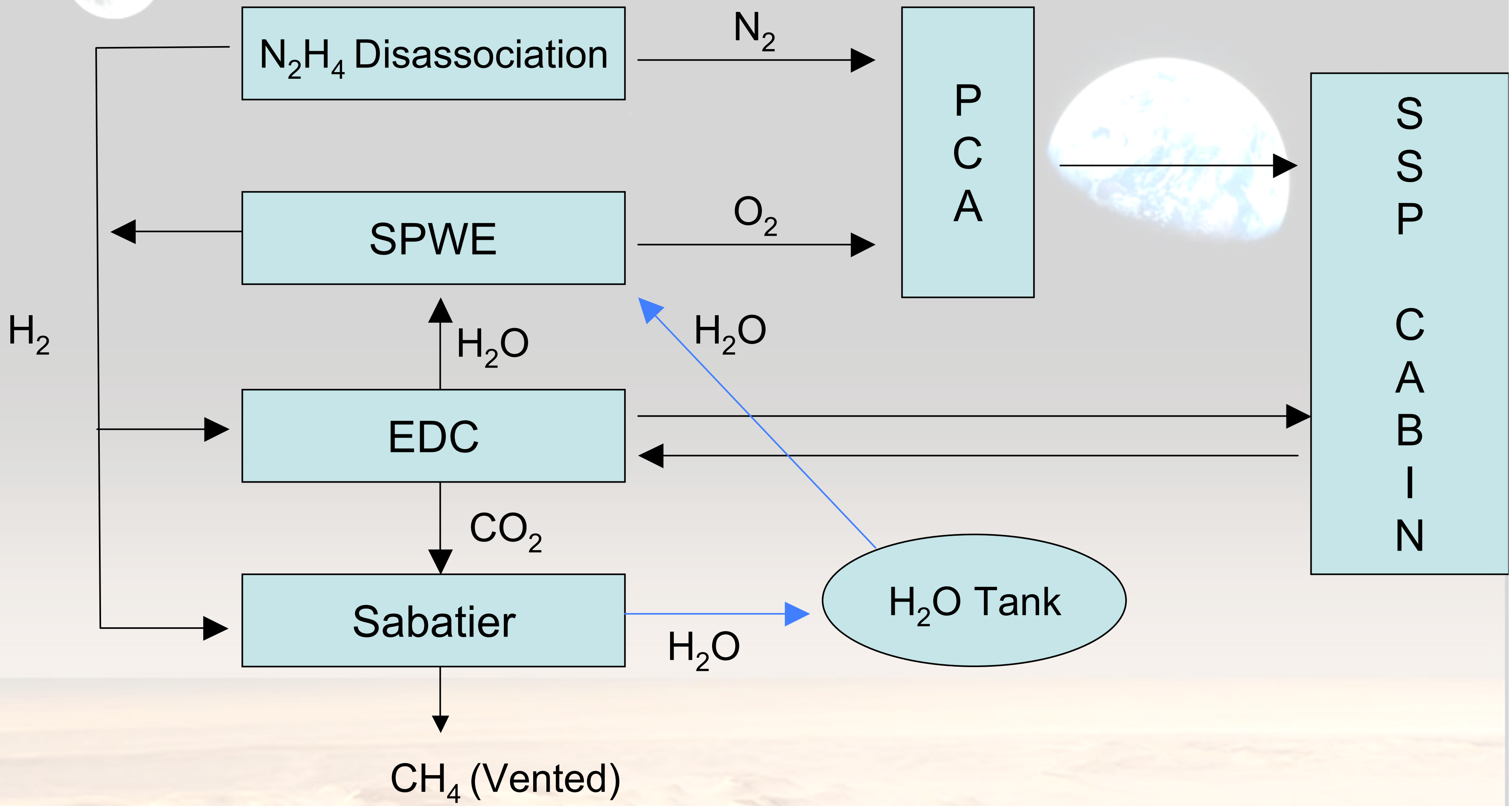
2. AR: Sabatier CO_2 Reduction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

- Needs H_2 from N_2H_4 and water electrolysis.
- On Oxygen Generation Rack
- Runs continuously at 99% single pass input/output efficiency.
- Produces methane (to be vented)

Daily CO_2 Reduction	6.14 kg-CO_2
Daily H_2O Production	4.88 kg-H_2O

2. AR: SPWE-EDC-Sabatier



2. AR: SPWE-EDC-Sabatier – H_2O

10.08 kg H_2O/day used by SPWE

4.88 kg H_2O/day produced by Sabatier

	Construction	Gravity Test	Mars Sim.
Crew Members	3	6	6
Stay Duration	180 days	300 days	900 days
ATMOSPHERE/OGS H_20 REQUIREMENT			
OGS Requirement	670 kg	1,560 kg	4,680 kg
28 Day Emergency	282 kg	282 kg	282 kg
Safety Factor	1.15	1.15	1.15
TOTAL H_20	**1,094 kg**	**2,118 kg**	**5,706 kg**

2. AR: Trace Contaminants

- Trace Contaminant Control Subassembly is on the AR Rack (TCCS)
- Components:
  - Charcoal Bed
  - LiOH Sorbent Bed
  - Catalytic Oxidizer
- Removes:
  - Acetaldehyde
  - Acrolein
  - Ammonia
  - CO & CO_2
  - Dichloroethane
  - Ethoxyethanol
  - Formaldehyde
  - Freon
  - Hydrogen
  - Hydrazine
  - Indole
  - Mercury
  - Methane
  - Methanol
  - Methyl ethyl keytone
  - Methyl hydrazine
  - Dichloromethane
  - Octamethyltrisiloxane
  - Propanol
  - Toluene

2. AR: Major Constituent Analysis

- MCA system monitors for O_2, N_2, CO_2, H_2, CH_4, and H_2O in entire cabin volume
- Consists of a mass spectrometer and a pump/valve system to cabin ventilation
- Located on AR Rack

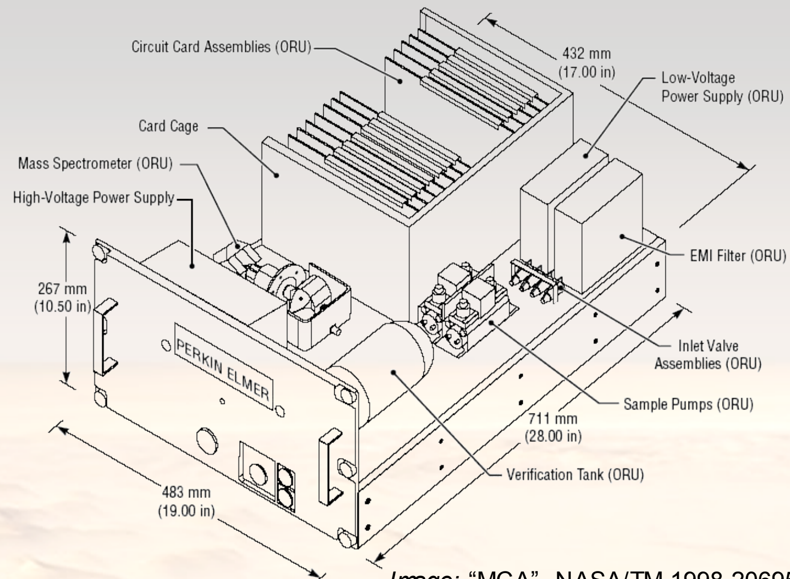


Image: “MCA”, NASA/TM-1998-206956/VOL1

3. Temperature/Humidity Control

- Removes moisture and heat from the atmosphere
- Circulation of the atmosphere
- Ventilation between modules (0.2 m/s)
- Removal of particulate contaminants
- Dissipates the 137 W of heat each crew member produces

3.THC-Common Cabin Air Assembly

Functions : Control the cabin air temperature, maintain the cabin air humidity level within limits, and generate ventilation air flow throughout the station

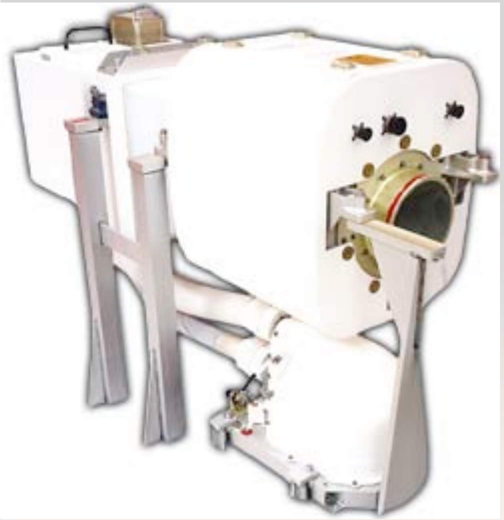


Image: "CCAA Graphic", Hamilton Sundstrand Space Systems International, 2005

Locations: Destiny Lab, Node 3A, Node 3B, U.S. Airlock, RM

Total Number: 12 (2 Spares)

	CCAA Mass (kg)	Power (kW)
Each	112	0.45
Total	1,344	3.15 (7 units on)

3.THC: Inter-Module Ventilation (IMV)

- Facilitated by existing ISS ducts built into the structure of the modules and nodes. (18) Include 2 in each tunnel

	IMV Fan Mass (kg)	Power (kW)
Each	4.8	0.06
Total (22)	105.6	1.32

- HEPA Filters allow cabin air filtration of particles and micro-organisms. Placed on IMV vents.

	Filter (kg)	Power (kW)
Each	2.14	0
Total (120)	256.8	0

Images: "IMV Fan Unit" and "HEPA Filter, Hamilton Sundstrand Space Sy stems International, 2005

3. THC: Module Ventilation Layout

Destiny, Node 3A, Node 3B, RM

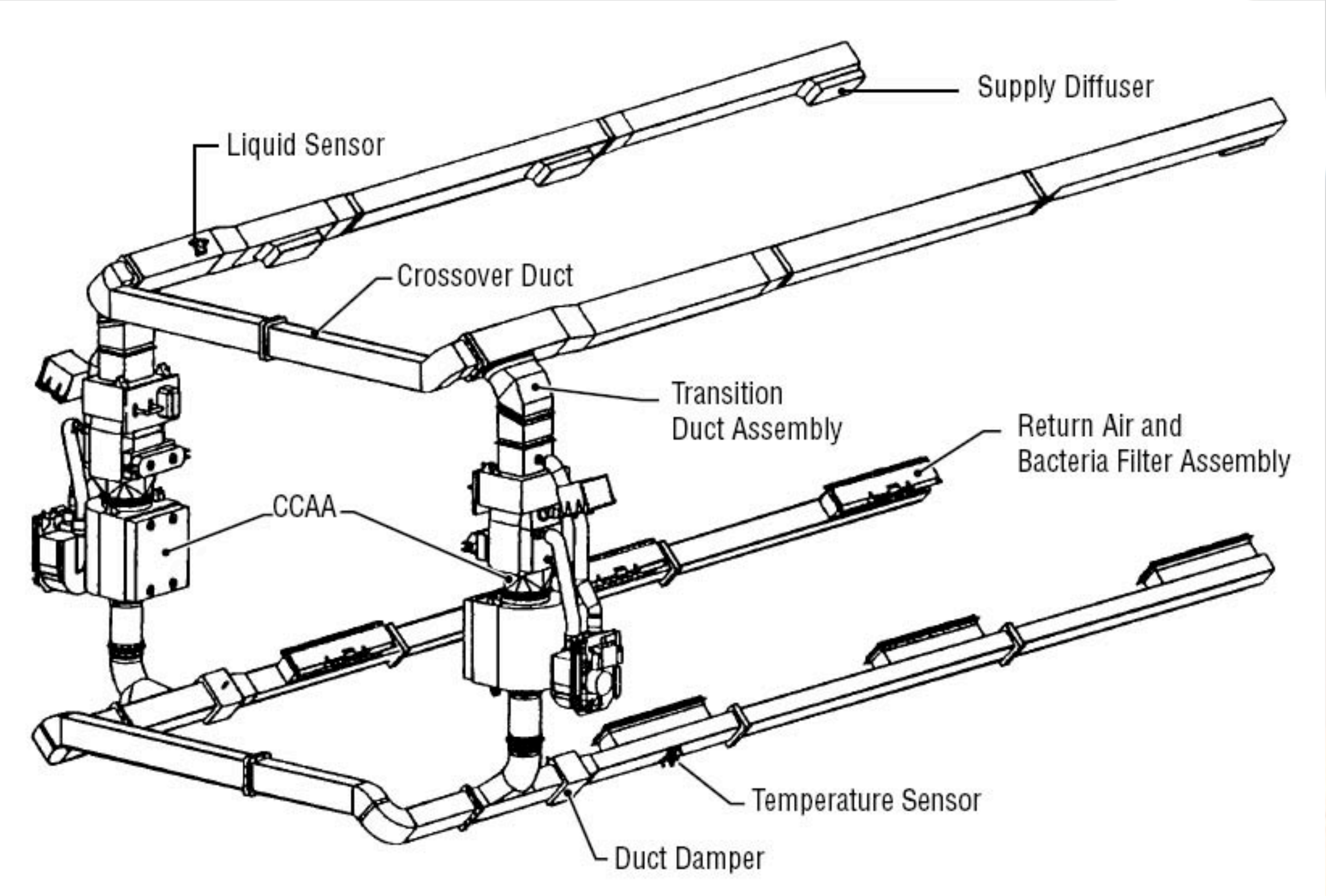


Image: "ISS AR Rack", NASA/TM-1998-206956/VOL1

Oxygen Generation Assembly

Image: "OGA Graphic", Hamilton Sundstrand Space Systems International, 2005

OGA Rack Statistics		
	Mass (kg)	**Power (kW)**
Total (All systems)	711	3.153

- OGA rack will combine **SPWE system** and **Sabatier CO_2 reduction system**
- OGA can produce 2.8 – 9.3 kg O_2/day
- Operates at 0.318 kW on standby, 3.153 kW in operation
- Made by Hamilton Sundstrand
- Primary: Townhouse A – Node 3A
- Secondary: Townhouse B – Node 3C
- Both units will run at 55% of full capacity

Atmosphere Revitalization Rack

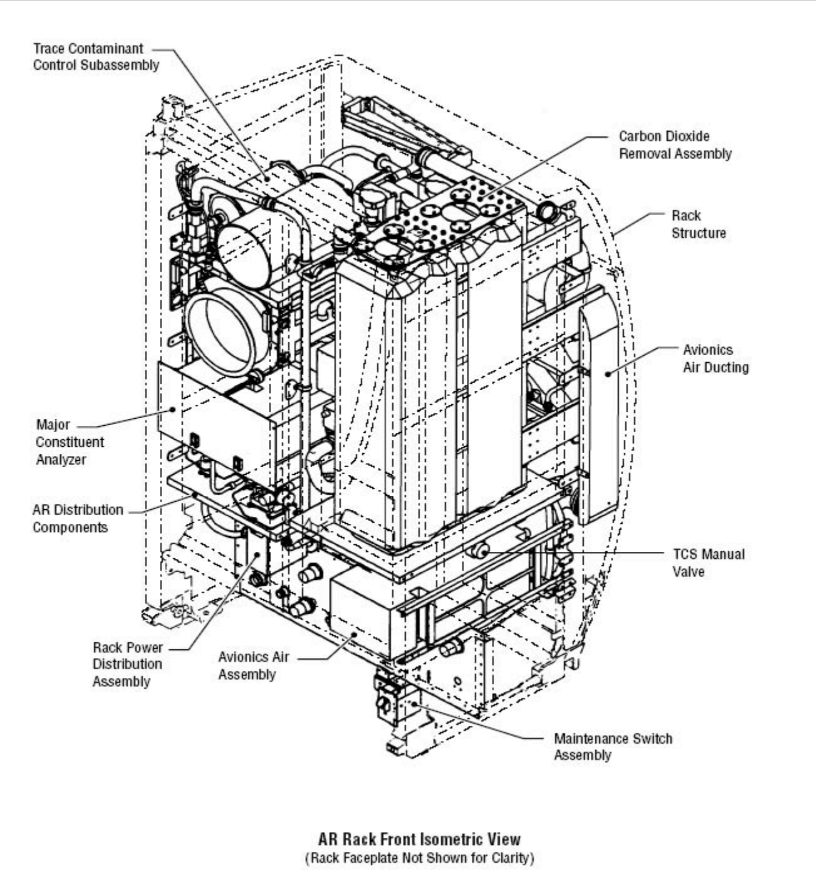


Image: "ISS AR Rack", NASA/TM-1998-206956/VOL1

AR Rack Statistics		
	Mass (kg)	**Power (kW)**
MCA	54	0.10
EDC	42	0.34
TCCS	78	0.24
Rack Equip.	300	1.22
Total Listed (All systems)	474	1.90

Two AR Racks on SSP:

- Node 3A
- Node 3B

Emergency O_2 Sources

Primary Backup: OGA Rack on opposite townhouse

Secondary Backup: Perchlorate "Candles" ($LiClO_4$)

One Canister = 1 day O_2/crew mbr.

Image: "Molecular Ltd." http://www.molecularproducts.co.uk/v2/products/candle_33/specs.htm

Supply	Units	Mass	Vol.
28 days	168	12.2 kg	0.012 m^3
TOTAL		2,100 kg	2.016 m^3

Third Backup: Portable Breathing Apparatus (PBA)

- Full face mask with 15 minute bottle of O_2
- 18 on SSP: 6 permanently on each townhouse, 6 designated as mandatory to carry when moving between inflatable transfer tubes

Image: "PBA", Whitaker, Overview of the ISS US Fire Detection and Control System

Emergency CO_2 Removal

Primary Backup:

- Auxiliary OGA/AR Racks in opposite townhouse

Secondary Backup:

- Lithium Hydroxide Absorption Canisters (LiOH)

2.1 kg LiOH / kg CO_2 absorbed

Image: STS-55 MS2 Precourt changes LiOH canister .
NASA PHOTOID-STS055-255-036

Supply	Units	Mass	Vol.
28 days	30	12 kg	0.012 m^3
TOTAL		360 kg	0.360 m^3

Fire on Space Station Phoenix

Dealing with a full/partial/zero-gravity cabin

- Zero-gravity
  - Atmosphere is non-convecting/diffusive
  - Hemispherical flames occur
  - Released CO is more toxic
- Partial/full-gravity
  - Atmosphere is convective, heat will rise
  - Atmosphere is non-quiescent

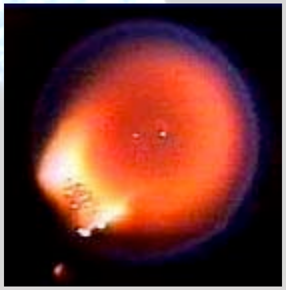


Image: Whitaker, Overview of ISS U.S. Fire Detection and Suppression System , JSC

Cut ventilation = Cut fuel (O_2) to the fire

Fire Detection

- Fire is detected by photoelectric smoke detectors on module/node cabin vents

Mass: 1.5 kg **Power:** 1.48 W **Units:** 30 (16 on orbit)

Image: Whitaker, Overview of ISS U.S. Fire Detection and Suppression System , JSC

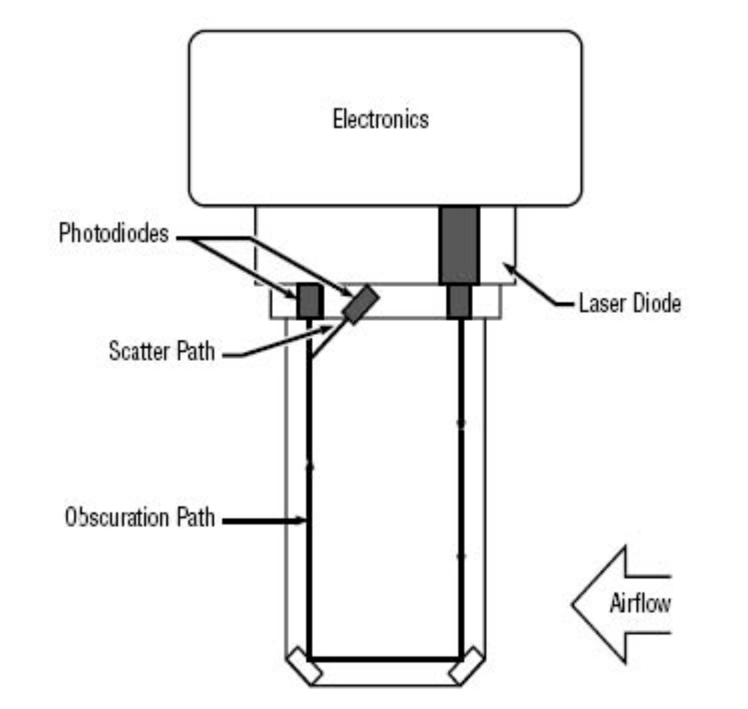


Image: NASA/TM-1998-206956/VOL1

Fire Suppression

1. **Put on PBA's**
2. **Turn off power and cabin ventilation to fire area**
3. **Extinguish fire using suppressant**

CO_2 Portable Fire Extinguisher (PFE)

Unit Mass	6.8 kg
Unit Volume	0.04 m^3
Discharge Time	45 s
Units on SSP	12

Source: Whitaker, Overview of ISS U.S. Fire Detection and Suppression System, JSC

3. **Remove/Purge contaminated module atmosphere (Activate a LiOH canister to neutralize excess CO_2)**

Cabin Depressurization

- Upon detection by pressure sensors, IMV will completely cease for affected module
- Pressure can be re-established gradually using automatic PCA controls or manual valves
- PBA masks must be donned immediately

Caution and Warning System

Crew is alarmed both audibly and visually to emergencies through:

1. Caution and Warning Panels

   Crew activated panels in each module that display either a fire warning, rapid change in pressure, atmosphere contamination, general caution and warning

2. Portable Computer Systems (PCS)

   Displays the exact nature and position of an emergency from cabin sensors

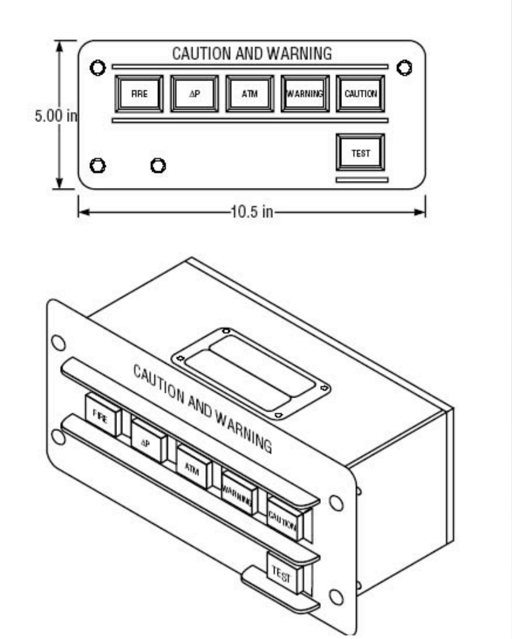


Image: NASA/TM-1998-206956/VOL1

Both systems are currently on the ISS, and will continue to be used on SSP

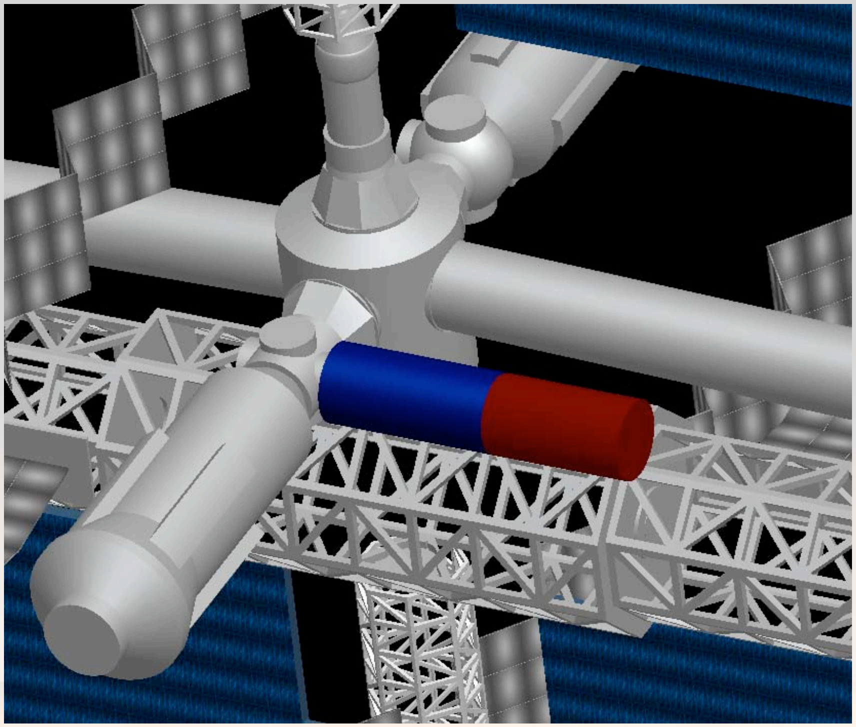
Total Life Support System Consumables

Maximum: Mars Simulation – 900 Days

Liquid H_2O	
Crew Living Provision	7,934 kg
OGS Provision	5,706 kg
H_2O Tank Mass	2,728 kg
Total H_2O Required	**13,640 kg**
Total H_2O Volume	**13.6 m^3**
Tank and H_20	**16,370 kg**

Liquid N_2H_4	
Nitrogen Leakage Replenishment	11,560 kg
N_2H_4 Tank Mass	2,312 kg
Total N_2H_4 Required	**11,560 kg**
Total N_2H_4 Volume	**11.4 m^3**
Tank and N_2H_4	**13,870 kg**

Crew External Tank Package



Liquid N_2H_4 Tank	
Volume	11.4 m^3
Radius	1.00 m
Length	3.64 m
Mass	2,780 kg (13,870 kg filled)

Liquid H_2O Tank	
Volume	13.6 m^3
Radius	1.00 m
Length	4.34 m
Mass	3,280 kg (16,370 kg filled)

Mission Profile

- Construction process
- Variable gravity experimentation
- Mars mission simulation

Image: http://www.smh.com.au/news/World/Spaceflight-made-simple/2004/12/21/1103391772373.html

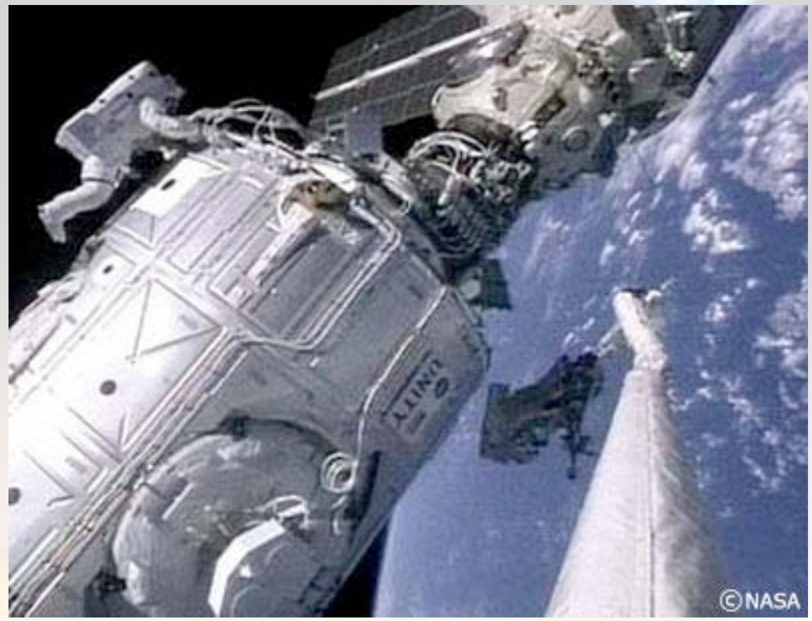


Image: http://spaceinfo.jaxa.jp/note/yujin/e/yuj9909_unity_e.html

Mission Goals

- Construct efficiently to allow enough time for other mission phases
- Perform variable gravity testing
  - Fresh crew for each test, in order to determine bone and muscle decay in gravity conditions other than Earth and microgravity
- Simulate Mars mission
  - Spin up station as quickly as possible to simulate landing on Mars surface

Science Objectives: Overall

- Level 1 Requirements
  - Mars surface EVA simulation
  - Quantify effects of variable gravity on human physiology
- Mission will allow for additional space research:
  - ISS provided microgravity reference for plant growth, cell biology, life science, human physiology, etc.
  - SSP will provide testing arena for similar experiments, using partial gravity levels, focus on Martian science simulation, mammalian response to partial gravity, and growth of edible biomass

Science: Payload Racks

International Standard Payload Racks (ISPR)

- "Refrigerator-Sized": 1.6 m^3
- Typically launched in MPLM, loaded in modules that accept ISPR: Columbus, JEM, Destiny

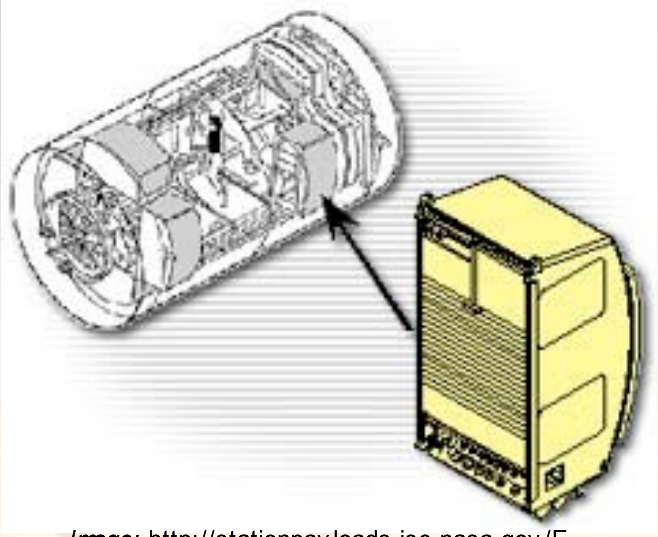


Image: http://stationpayloads.jsc.nasa.gov/E-basicaccomodations/E1.html

Science Module: Destiny

- 24 racks total (6 on each side)
  - On ISS: 11 racks for crew systems , 13 racks dedicated to scientific endeavors (mostly on “walls”)
- On SSP:
  - 1 rack: Human Research Facility (HRF) 2
    - HRF1 is with exercise equipment in Raffaello MPLM
  - 1 rack: Microgravity Science Glove Box
  - 1 rack: Plant Biotechnology Facility
  - 1 rack: Mars research equipment tests
  - 3 racks: Mammalian Research Facility
  - 1 rack: HRF sample stowage
  - Remaining racks re-allocated to crew systems

Image: http://www.boeing.com/defense-space/space/spacestation/components/us_laboratory.html

Science Module: Columbus

- On ISS:

  10 racks available for science

- On SSP:

  10 racks dedicated to Mars EVA simulation

Image: http://www.esa.int/esaHS/ESAAYI0VMOC_iss_0.html

Science Module: JEM-PM "Kibō"

- On ISS:
  - 23 racks total (10 racks for science, 13 racks for systems/storage)
- On SSP:
  - 3 racks: Japanese Multi-user Experiment Facility (MEF)
  - 1 rack: experiment container storage
  - Remaining racks allocated to crew systems

Science: HRF

- Two facilities: HRF 1, 2
  - Support various tasks
  - Each HRF contains modular experimental equipment for ideal location capability
- Study human adaptation to partial gravity (some of this done during exercise using HRF 1)
  - Cardiopulmonary: heart and lungs
  - Musculoskeletal: growth and maintenance of muscle and bone
  - Body systems regulation: homeostasis
  - Radiation Effects
- Requires stowage of samples: 1 rack

http://hrf.jsc.nasa.gov/
http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/hrffact.pdf

Image: http://hrf.jsc.nasa.gov/

Science: HRF (cont.)

Research Equipment:

- Activity Monitor: worn on wrist, study sleep quality, daily activities
- Ambulatory Data Acquisition System: vital signs
- Ultrasound: imagery useful in studying blood flow to vital organs, transmitted to Earth for analysis
- Continuous Blood Pressure Device: worn on fingertip
- Foot/surface contact force measurement
- Hand Grip Dynamometer: measure hand strength
- ECG (electrocardiogram): track heart rate
- Space Linear Acceleration Mass Measurement: track crew body mass
- Instruments for collecting blood, urine, saliva, etc., centrifuge for body fluid study

Science: MSG and PBF

- Microgravity Science Glove Box
  - Sealed work area for experiments
  - Keeps particulates, debris, fumes from entering SSP atmosphere or soiling the area at any gravity level

Image: http://www.esa.int/esaHS/ESAJVYG18ZC_research_0.html

- Plant Biotechnology Facility
  - Plant growth in regulated environment to test capability to create edible biomass under varying conditions
  - Features glove box area for isolation from plant matter
  - Normally mounted in EXPRESS rack, shared with other equipment, but will have additional chamber capabilities and use an entire rack space

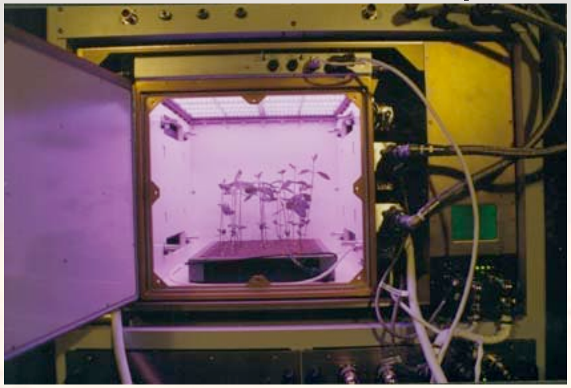


Image: http://wcsar.engr.wisc.edu/cpbf.html

Science: Mars Equipment Test

1 rack in Destiny dedicated to small-scale testing of potential Mars equipment

- Test in Martian gravity, atmosphere
- Test systems required to process Martian soil, geology, and atmosphere to produce propellant and refine oxygen
- Test solar array wiping equipment and study dust settling effects in simulated dusty Martian atmosphere
- Test sensors, sensitivity deterioration, errors
- Basic long-term endurance and functionality tests

Science: Mammalian Research Facility

3 racks for storage and study of research laboratory rats

- 72 rats available for experiment and control
- Study breeding and physiological effects of partial gravity
  - With new births, scientists will be able to study rats that have never experienced particular levels of gravity.
- Systems available for anesthesia, restraint, respiration and heart rate monitor, autopsy, bone density measurement, glove box for scientist interaction (possibly including rat “maze” test)
- Effective, humane use of entire rat lifespan
- Safe containers for corpse disposal without exposure to SSP atmosphere
- Utilize freezer in MEF for sample storage until return to Earth for analysis

Image: http://www.med.umich.edu/opm/newspage/images/Rat_(012).jpg

Science: MEF

Multi-user Experiment Facility

- Selected components
- Life science: cells, microorganism cultivation
- Centrifuge for 1g control experiment
- Clean bench to prevent contamination (glove box)
- Microscope
- Aquatic chamber for vertebrate growth/breeding
- Image processor for experiment image relay to Earth
- Freezer: -80 °C

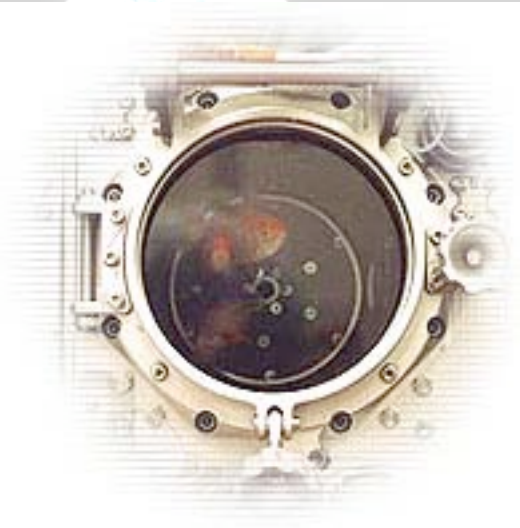


Image: http://stationpayloads.jsc.nasa.gov/F-facilities/f3.html

Science Mission Accomplishments

Studies in:

- Human physiology in partial gravity
- Rodent physiology in partial gravity
- Biology (plant growth, cell biology)
- Mars equipment reliability and robustness

Main Radiation Sources

Main contributors to radiation exposure

- Galactic Cosmic Radiation (GCR)
  - Continuous high energy radiation
  - Maximum intensity at solar minimum
- Solar Particle Events (SPE)
  - Periodic high intensity solar radiation spikes
    - Coronal mass ejections
    - Solar flares
  - Most frequent during solar maximum

Radiation Exposure Limits

Dose Equivalent Limits

	BFO (Sv)	Eye (Sv)	Skin (Sv)
Career	*Varies*	4.0	6.0
1 year	***0.50***	2.0	3.0
30 day	0.25	1.0	1.5

NCRP Report No. 132 (2000)

Deep Space Radiation

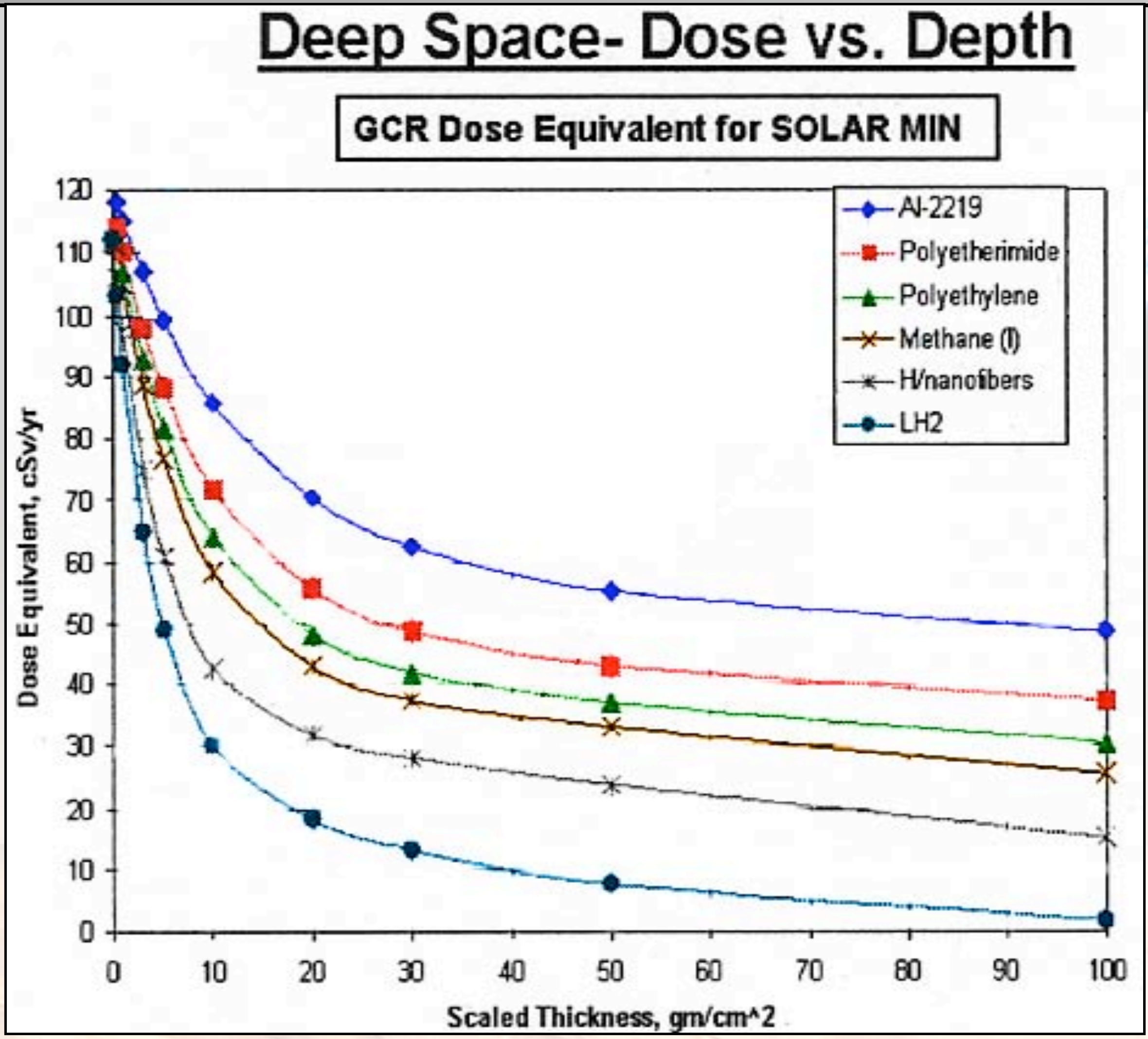


Image (Modified from original) : Atwell, William. "Spacecraft Design Considerations for human Radiation Shielding and Protection Issues." AIAA SPACE 2005 Conference. Long Beach, CA. 2005.

Deep Space Radiation Shielding

- Primary shielding
  - 18 g/cm^2 polyethylene relative thickness
  - 0.5 Sv/yr (GCR)
- Beds sheltered against SPE
  - 35 g/cm^2 polyethylene relative thickness
    - 17 g/cm^2 additional
  - 0.4 Sv/yr (GCR)

Deep Space Shielding Mass

- Mass of bed shelter

  8,000 kg

- Primary shielding

  239,000 kg

  (inflatable transfer tubes, central axis, and JEM-ELM PS not shielded)

- Total radiation shielding for deep space

  247,000 kg

Cost for Deep Space Mission

- Cost to launch radiation shielding

  $2.47B

- Propellant launch cost to boost station to L1 (including estimated radiation shielding)

  $10.77B

- Total additional cost for L1 mission

  $13.24B

Low Earth Orbit

- Deep space environment too severe for budget limits
- LEO station saves $13.24B in launch costs
- Station components already shielded to LEO radiation environment
- Overall exposure rate for ISS is approximately 0.3 Sv/yr
- Beds will be built out of polyethylene to further reduce overall exposure

Proposal to Meet Goals

- LEO environment fails to meet Level 1 Requirement # 9
- Separate unmanned research mission will be required
  - Study overall deep space radiation environment
  - Test effectiveness of shielding strategies in deep space

Proposal to Meet Goals

- Small capsule with various radiation experiments
  - Dosimeters scattered throughout the capsule
  - Phantom torsos in various conditions
    - EVA suit
    - Several small scale shielded boxes
  - Small biological experiments
- Capsule will be sent to L1 for duration of mission

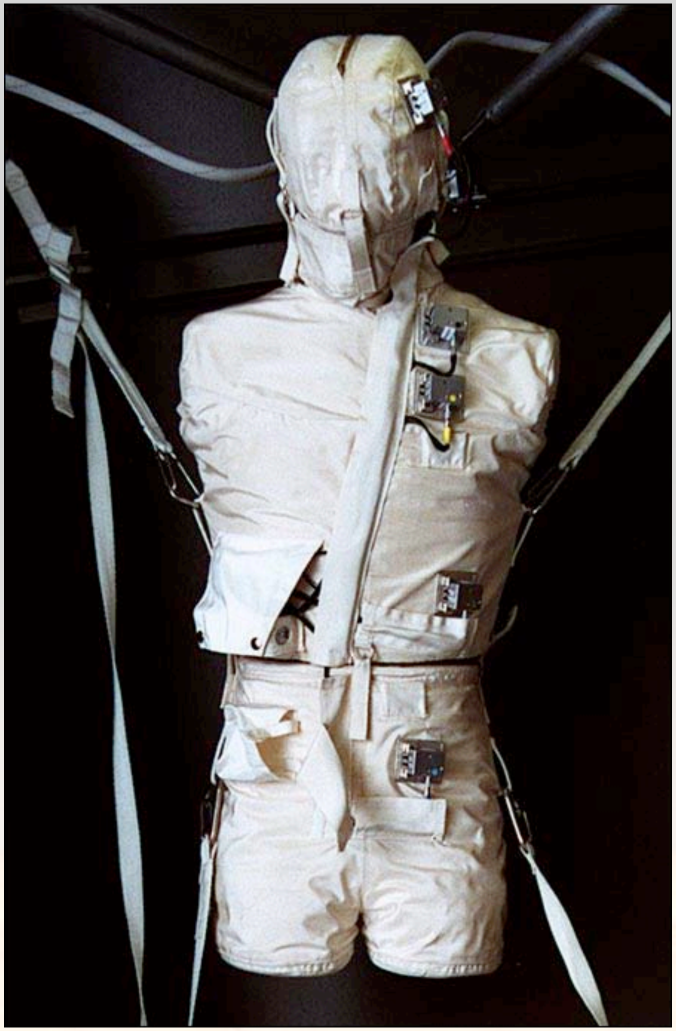


Image:
http://ds9.ssl.berkeley .edu/LWS_GEMS/5/images_5/phantor.jpg

Transport – Phantom Torsos

- Three restartable upper-stage engines considered

Engine	Maker	ISP (s)	Mass (Kg)	Thrust (KN)	Propellants
RL-60	Pratt and Whitney	465	499	289	LOX/LH2
Merlin	SpaceX	304	434	409	LOX/Kerosene
MB-60	MHI / Boeing	467	591	267	LOX/LH2

- All three are still in development but have been tested to different degrees
- LOX/Kerosene is cleaner, but mass of propellant needed is about twice the mass needed for MB-60 or RL-60

Transport – Phantom Torsos

- RL-60 chosen to balance mass and cost of propellant launched
- RL-60 Characteristics
  - Cryogenic propellants
  - Expander cycle
  - Same size as RL10B-2 with twice the thrust
    - Length = 3.8 m
    - Diameter = 2.13 m

Image: www.pratt-whitney.com

Estimated Cost of Proposed Mission

Launch cost of capsule (23,000 kg capsule)	$230M
Launch cost of boosting propellant	$379M
Total launch cost	$609M
Estimated development costs	$985M
Estimated first unit cost	$344M
Total estimated cost of proposed mission	**$2.55B**

Overall Advantages of LEO

- $10.67B saved by NASA (including proposed mission)
- $13.24B saved by SSP
- Higher safety for astronauts
  - Less radiation
  - Quicker return to Earth
- Simpler to exchange crews and re-supply station
- Simpler communication systems

Variable Gravity Constraints

- Level 1 requirement: SSP shall be used to quantify the effects of variable gravity on human physiology to allow the design of Mars transit vehicles by Jan. 1, 2024 (#5)
- Budget

  Once SSP is constructed, only one re-supply mission per year can be afforded
- Time required for construction and Mars Mission Simulation phases

Variable Gravity Testing

- Important to determine a region of gravities for easily maintaining muscle/bone mass
- Number of gravity levels between 0 and 1g constrained by budget, construction time, and required time for MMS
- Crew re-supply transfer time
  - Should allot time for transfer, docking, and re-supply
  - Amount of time at each gravity level
  - Just enough time to become acclimated to gravity vs. longer periods to study effects

Variable Gravity Options

- One crew at multiple gravity levels
  - Pro: Can possibly do more gravity levels
  - Con: Effects of transitioning from new gravity to the next could be dangerous
- Multiple crews (fresh at each level)
  - Pro: Fresh “control” group at each level
  - Con: Crew must be launched to station
- Type of gravity levels (low, high, both?)

Facts Regarding VGT

- CEV must be replaced each year for safety considerations
  - If CEV needs to be replaced, why not crew?
- Unknown gravities → Unknown problems
  - Subjecting individual crew members to various levels of gravity potentially dangerous
- Budget is a strict limiting factor

VGT Overview

- 3 chosen gravity levels (¼, ½, ¾g)
  - 10 months at ¼ and ½g
  - 9 months at ¾g so budget and time constraints can be met
  - Maximum Russian experience in microgravity was close to 1 year
- Crew re-supply after each experiment
- Test operability of SSP before Mars Mission Simulation

Variable Gravity Timeline

Date	Mission	Duration	Gravity (g)
July 1, 2021	Crew Transfer	1 week	0
July 8, 2021	Spin up	6 hours	0→¼
July 8, 2021	G exp. 1	10 months	¼
May 8, 2022	Crew Transfer	1 week	¼
May 15, 2022	Spin Up	3 hours	¼ →½
May 15, 2022	G exp. 2	10 months	½
Mar. 15, 2023	Crew transfer	1 week	½
Mar. 22, 2023	Spin up	2 hours	½ →¾
Mar. 22, 2023	G exp. 3	9 months	¾
Dec. 22, 2023	Spin Down	11 hours	¾ →0
Dec. 22, 2023	Crew Transfer	>1 week	0

Mars Mission Simulation

- Level 1 requirement: SSP shall be capable of performing a full duration simulation of a Mars mission without re-supply (#1)
- Important for determining effect of a mission to Mars on the human body
- 3 years total as per NASA reference mission (Fast Transit Option)
- 0g transit phases as per NASA reference mission

MMS Option 1 : Short Stay

- 7.5 month transit phase
- 1 month Mars phase
- 10 month return phase
- Advantages
  - Least overall time outside of Earth for astronauts
- Disadvantages
  - High cost for low Mars gravity experimentation
  - High risk, astronaut adaptation in 1 month unknown

MMS Option 2: Long Stay

- 7.5 month transit phase
- 15 month Mars phase
- 8 month return phase
- Advantages
  - Enough time for astronaut recovery
- Disadvantages
  - Overall long microgravity time, adaptation may be difficult

MMS Option 3: Fast Transit

- 5 month transit phase
- 21 month Mars phase
- 4 month return phase
- Advantages
  - Shortest transfer phase
  - Time in microgravity is comparable to tours of duty on the International Space Station
  - Maximizes Mars gravity experimentation
- Disadvantages
  - Long stay in Mars gravity may be detrimental to bone regeneration

MMS Options

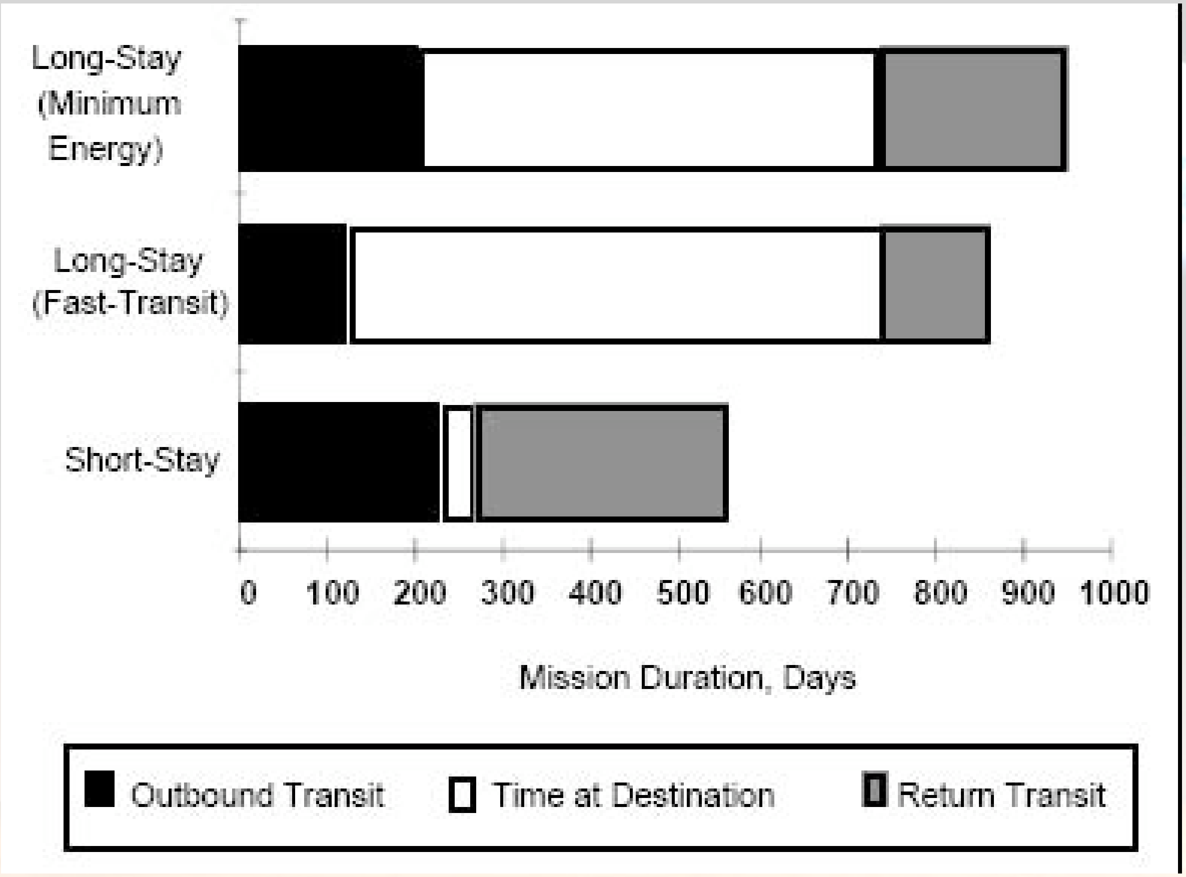


Image: Stephen J. Hoffman and David I. Kaplan, eds., *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team* - NASA SP-6107 - NASA Johnson Space Center, July 1997. pg 122.

MMS Overview

- Crew arrives in January 2024, as last VGT crew leaves
- Station can be configured and prepped during 5 month 0g transfer phase
- Crew transfer to and from station are included in transfer and return phases to save on time in case of emergencies
- Total time: approximately 2.5 years

MMS Timeline

Date	Mission Phase	Duration	Gravity (g)
Jan. 1, 2024	Transfer Phase	5 months	0
Jun 1, 2024	Spin Up	8 hours	0 → ⅜
Jun 1, 2024	Mars Gravity phase	21 months	⅜
Mar. 1, 2026	Spin Down	8 hours	⅜ → 0
Mar. 1, 2026	Return Phase	4 months	0
July 1, 2026	Mission Complete	------------------	------------------

Mars EVA

- The goal of Mars EVA simulation is to prepare the crew for a 600 day stay on Mars surface
- 2 crew members will suit up in a full Mars EVA suit for 6 hours a day, resulting in about 12 hours of EVA time a week for each crew member
- Entire simulation will take place in Columbus, with the module being designed to simulate Mars gravity and atmosphere to prepare crew for a Mars surface mission

Mars EVA

- Upon entering the habitat, the crew members will suit up into Mars EVA suits
- For the first hour of training, crew will become comfortable with suits
- Crew will acknowledge amount of time it takes to suit up as well as any flaws in the suit
- Crew will then test their visibility while in the suits
- For the last part of the hour, the crew will spend their time walking around the habitat, bending, squatting, and carrying items from one side of the habitat to the other

Image: http://www.ilcdover.com/products/aerospace_defense/pdfs/Evaluation%20of%20a%20Rear%20Entry%20System%20for%20an%20Advanced%20Spacesuit.pdf

Mars EVA

- 2 racks: One treadmill with virtual reality system in crew habitat
- 1 rack: Rover simulation with virtual reality system
- 1 rack: Tool work station (1 rack)
- 2 racks : Sandbox (2 racks)
- 2 racks : Suits
- 1 rack : Storage

Mars EVA

- One crew member will walk on the treadmill at various inclinations and speeds for a period of two hours
- Virtual reality system will be provided for the crew in order to provide a realistic Martian experience
- This task will increase the crew's strength and maneuverability in the suits

Image: http://advlifesupport.jsc.nasa.gov/ehti3/treadmill.html

Mars EVA

- One hour devoted to operating a rover simulation
- Crew provided with rover prototype, as well as a program that simulates the rover on Mars' surface
- The crew will simulate maneuvering the rover on Martian surface as well as collecting samples

Image: http://spacecraft.ssl.umd.edu/design_lib/TP01-209371.Mars_surfaceDRM.pdf

Mars EVA

- One hour devoted to tasks in the tool work station
- One task putting together small nuts and bolts to improve crew dexterity in the suit gloves
- The crew will also have projects where they will have to assemble a small item and will work their way up to more difficult projects

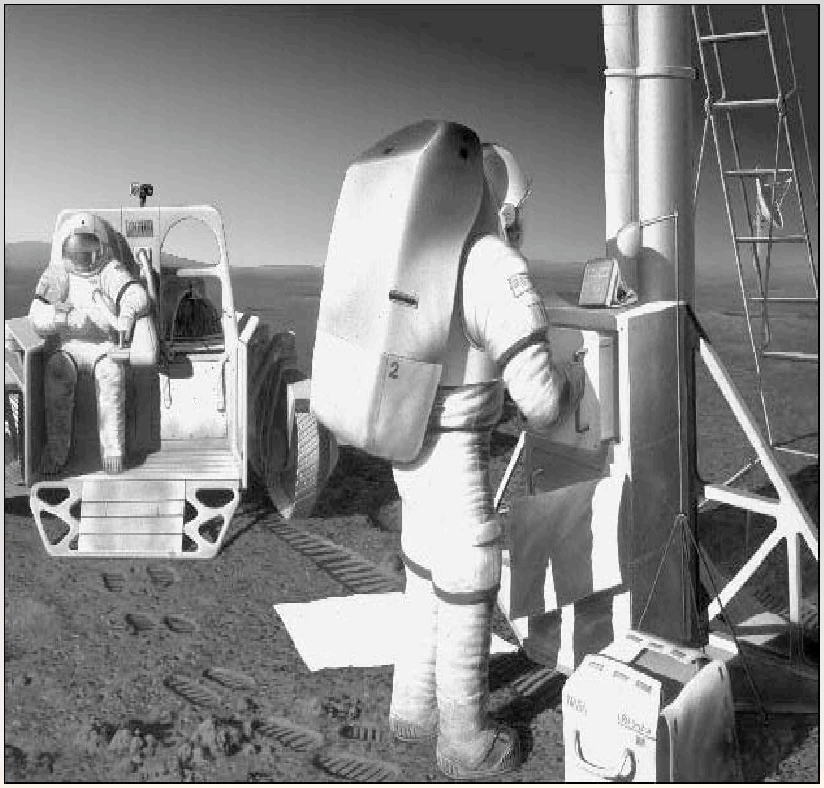


Image: http://spacecraft.ssl.umd.edu/design_lib/TP01209371.Mars_surfaceDRM.pdf

Mars EVA

- Final hour devoted to the sandbox
- Sandbox will simulate field work that the crew will conduct while on Martian surface
- Main activity will be collecting samples of dirt and rock as well as becoming proficient with the tools for collection
- The crew will also become adept at setting up radar and seismic detectors in the dirt
- The crew will also become skillful in maintaining an environment that is highly susceptible to dirt and dust

Image:
http://spacecraft.ssl.umd.edu/design_lib/TP01209371.Mars_surfaceDRM.pdf

Mars EVA Simulation Suit

- 2 Suits for Mars EVA
  - I-Suit (ILC Dover)
    - Soft Upper Torso
    - Rear Entry
    - Operating Pressure Difference
      4.3 psi
    - Mass
      37.1 kg each
  - ISS EMU PLSS
    - Same life support system as ISS EMU
    - Mass
      63.6 kg each
- Total mass : 201 kg

Image: http://spacecraft.ssl.umd.edu/

Mars EVA Simulation Suit (cont.)

Suit atmosphere

- Pressure
  - 4.3 psi above cabin pressure
- Consistency
  - Pressurized cabin nitrogen/oxygen atmosphere
- Denitrogenation (based on Dive Tables)
  - 4.3 psi pressure increase, equivalent to approximately 3 m water depth
  - Up to 797 min (13.3 hrs) of safe work time without needing staged decompression, so long as there are 12 hours between EVA simulations

External EVA Suit

- 3 – ISS EMU Suits
  - 102 kg each
  - 0.66 m x 0.71 m x 1.02 m storage size
  - Proven design
- 3 – ISS EMU PLSS
  - 63.6 kg each
- Total mass : 497 kg

Image:
http://www.nasa.gov/multimedia/imagegallery/image_feature_382.html

External EVA Operations

- External EVAs will utilize the US Airlock
  - Station spin will be stopped for any external EVA
- 60+ minute suit checkout before EVA
- 6 hour work time for EVAs with no umbilical
  - 15 min to egress from airlock
  - 15 min to ingress to airlock
  - 30 min reserves
- Depressurization / Repressurization
  - Max. rate of 0.05 psi/s
  - Emergency repressurization. 1.0 psi/s

External EVA Denitrogenization

- Nominal 4 hour O_2 pre-breathe in suits
- Experiments on reducing pre-breathe times
  - Reducing cabin pressure 12 to 36 hours before an EVA
    - Reduces N_2 partial pressure, reducing N_2 in blood
    - 10.2 psi nominal “camp-out” pressure
    - Can to reduce pre-breathe to 40 minutes after 36 hours
    - Risk to fan-cooled electronics limits extent of depress
  - Moderate exercise during pre-breathe period

Post EVA Maintenance

- Metrox CO_2 scrubber recharge
  - Baked for 14 hours in US Airlock oven
  - 55 cycle limit over nine years
  - O-ring replacement every 27 cycles
  - Will have LiOH back-up canisters
- Battery recharge
  - 32 cycle limit
- O_2 and water recharge

Long Term Maintenance

- Every 85 days
  - Battery maintenance
- Every 180 days
  - Dump and refill of half the feedwater supply
- Every 369 days
  - Mid-term checkout with a two hour fan run time

Astronaut Composition

Command, control, and operations

- Pilots (2)
  - Commander, CEV flight control
  - Station control operations
  - Ground communications, crew leadership
  - Responsible for crew safety, mission success
- Engineer (1)
  - CEV upkeep
  - Onboard systems maintenance
  - Mission objective support
  - Oversee any additional construction or repairs

Astronaut Composition

Scientific and Habitability Operations

- Scientists (2)
  - Oversee/perform experiments
  - Majority of EVA simulation work
  - Secondary medical assistance
- Astronaut Physician (1)
  - Designated crew medical officer
  - Examines effects of variable gravity environment on human physiology
  - Provides medical care to crew, under direction of a ground-based specialist if necessary

Astronaut & CEV Rotation

- Current ISS protocol requires annual replacement of Soyuz vehicle
- Construction and variable gravity phase
  - Crew rotations will occur at least annually
  - Crew will arrive and depart on the same CEV
  - CEV will remain docked on station as emergency "lifeboat" during mission
  - Any necessary re-supply could take place during these rotations

Astronaut & CEV Rotation

- Mars Mission Simulation phase
  - CEV will be swapped twice during mission
  - Due to requirements, no re-supply of consumables or crew will take place
  - Exceptions:
    - Critical consumable replacement
    - Station upgrades or repairs
    - Crew swap motivated by medical emergencies

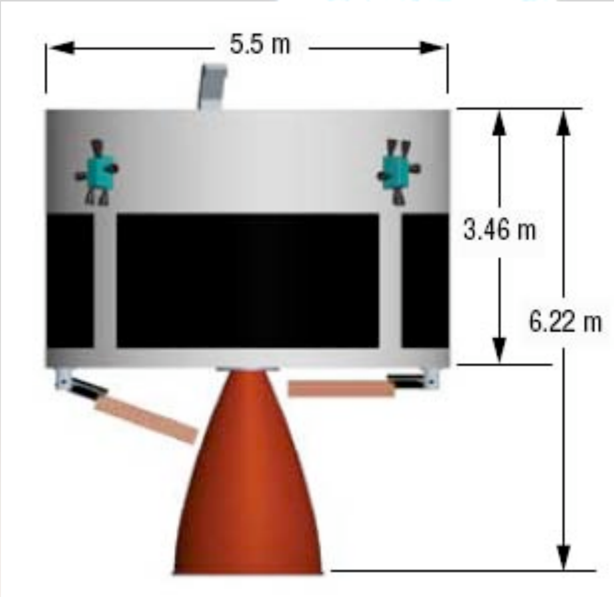
Crew Exploration Vehicle

- Transfer and return crew from Earth to SSP
- Provide emergency escape from SSP
- CEV docking
  - APAS-compatible
  - Docking adapter on orbit on ISS (PMA)
- CEV designed to be reconfigurable
  - Accommodate a crew of six
  - Direct applications to (SSP) missions without significant changes in the vehicle design

Crew Exploration Vehicle

- CEV

- Service Module (SM)
- Crew Module (CM)



Avionics

The CEV CM avionics subsystem provides Command and Control (C&C)

- Command, Control, and Data Handling (CCDH)
- Guidance and navigation
- Communications
- Cabling and instrumentation

CM Avionics

- 4 flight critical computers
  - Two fault tolerant processing
- 8 data interface units
- 2 multifunction LCD & 2 control panel sets
  - Provide a crew interface for system status and command input
- 2 sets of translational/rotational/throttle hand controllers
  - Provide manual vehicle flight control

CM Avionics

- Provide on-orbit vehicle attitude information for the CEV
- Perform guidance and navigation processing
- Execute AR&D
  - Global Positioning System (GPS)
  - Inertial Navigation System (INS)
    - 4 GPS antennas
    - 2 star trackers
    - 2 video guidance sensors
    - 2 3-D LADAR units to provide AR&D

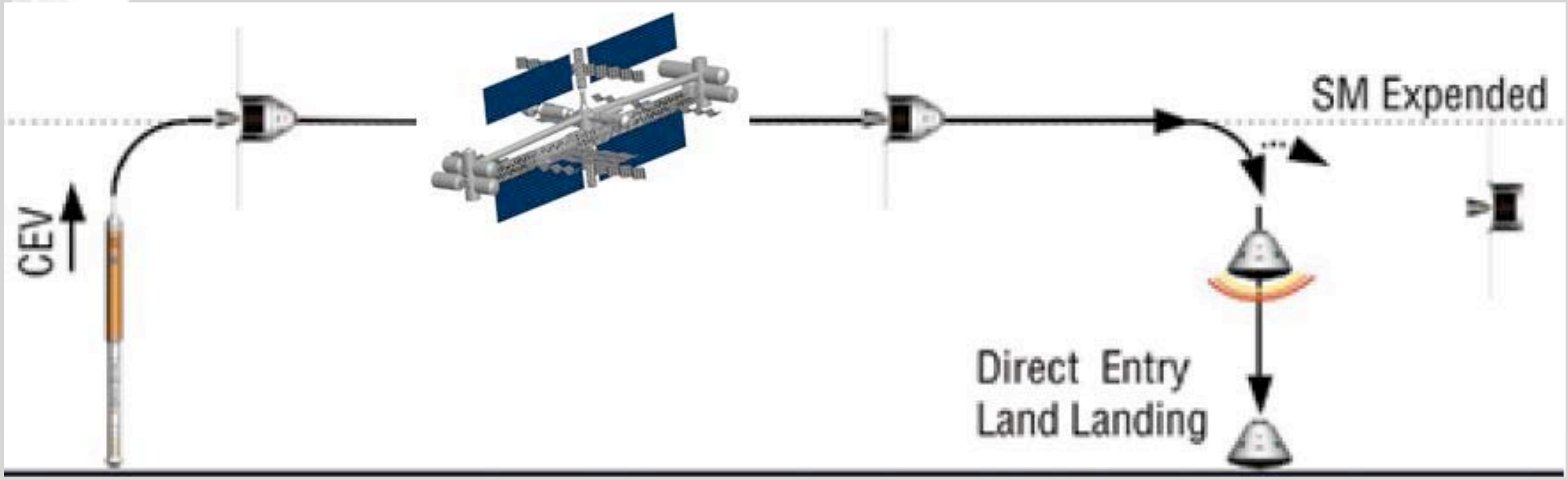
Communication and Tracking

- Provide communications and tracking from other architecture elements to the ground
- Information on the communication links
  - Command
  - Telemetry
  - Voice
  - HD video
  - Payload data
- Assumed communications components
  - S-band/Search and Rescue Satellite aided Tracking (SARSAT)
  - Ultrahigh Frequency (UHF)
  - Network signal processors
  - Information storage units
  - Operations recorder

Docking

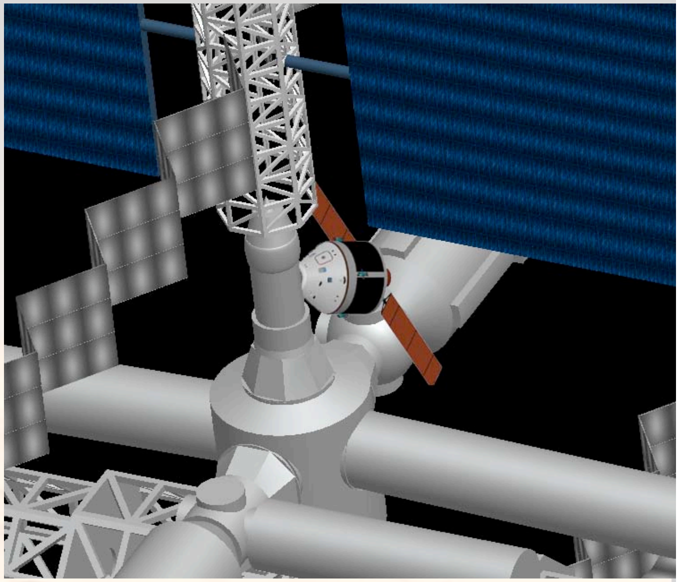
- Orbit Insertion
- Execute AR&D
  - 2 video guidance sensors
  - 2 3-D LADAR units to provide AR&D
- Manual rendezvous and docking
  - 2 sets of translational/rotational/throttle hand controllers
  - Remote Manipulator System
  - SSP-CEV UHF communication

Sequence



LADAR units to provide AR&D

CEV docked to SSP



LEO Launch Parameters

- One daily launch window from NASA/KSC
  - SSP must be going from south to north in the earth's plane
  - Launch window: ~5 min
  - Launch $\Delta V > 7.7$ km/s
- De-orbit window occurs several times per day, based on established landing zone
  - Deorbit $\Delta V \approx 115$ m/s

Emergency Protocol

- Minor health emergencies
  - Attended to by on-board physician, under direction from ground specialist if necessary
  - Individual will be replaced during next crew rotation opportunity
- Temporary environmental emergencies
  - Portable breathing apparatus, EVA suits
  - Module isolation
  - CEV retreat
- Permanent/severe emergencies could require station evacuation or rescue mission

Emergency Evacuation

Option would be implemented for critical SSP failure

Operation	Time Required	Comments
EVA Suit (optional)	15-20 minutes	Would only be required if crew transfer environment was deemed hostile
Transfer to CEV	4-6 minutes	From anywhere in the station, docked CEV should be accessible in this time, based on 0.15 m/s climb rate
CEV Departure	< 1 hour	CEV will be maintained flight-ready at all times, and capable of supporting crew until return mission
Completed Emergency Evacuation	< 2 hours	Very small time required in station if safe evacuation environment exists

Rescue Mission

Option would be implemented for critical CEV failure or necessary crew member exchange ("Life or Limb")

Operation	Time Required	Comments
Prepare Rescue Mission	≤ 14 days	CEV will be designed to be launched on pre-existing launch vehicles, allowing a much shorter turn-around time than the Shuttle (14 days was fastest back-to-back launch time, occurred in 1995)
Launch Mission	< 24 hours	One-per-day launch window to SSP orbit, assuming passable launch conditions exist
Crew Rescue	20 min - 4 hours	Dependant on docking location, crew conditions, etc.
Completed Rescue Mission	≤ 16 days	28 days of contingency supplies for astronauts; rescue mission possible

Emergency Station Access

- Alternative docking/access point will be available on Townhouse A
  - Use of this point will require spinning down the station (maximum ~ 11 hours)
  - Given the time to launch a rescue mission to LEO, this would not be an issue
- Point could potentially be used as EVA “bailout” location in critical environment situation

Rescue Vehicle

- CEV used as rescue, crew rotation vehicle and supply vehicle
- Required to be docked for up to one year
- Internal CEV propulsion will contain storable propellants (such as N_2O_4/UDMH) or LOX/LH_2
  - Storables are highly toxic but can be stored for years
  - LOX/LH_2 boils off over time
- If LOX/LH_2 is chosen, CEV must be designed to hold sufficient propellant or extra tanks must be launched and stored on station

Atmospheric Re-entry

- RCS used to place CEV in right trajectory
- CEV to re-enter Earth's atmosphere and land
- Land-based landing in CONUS
- Need to lower orbit from to an altitude from 340 km to 50 km above Earth
- Entry to 50 km orbit at a flight path angle of -2°
- Requires a ΔV of ~ 115 m/s

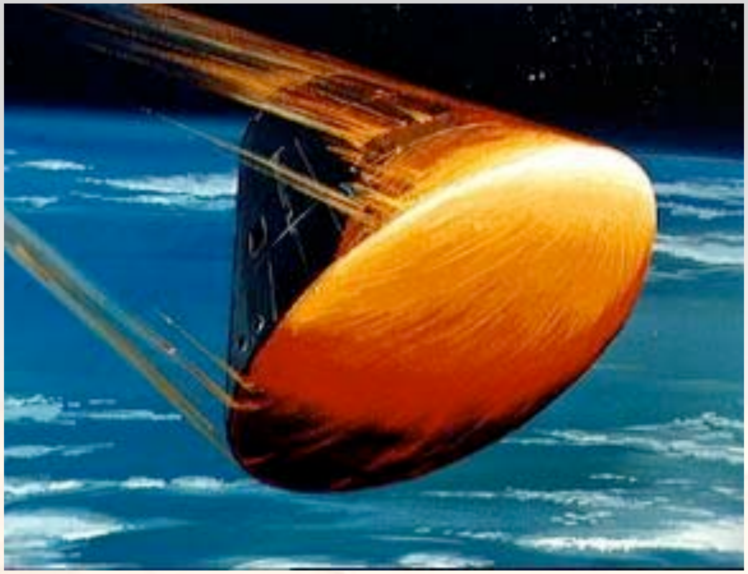


Image: http://en.wikipedia.org/wiki/Atmospheric_reentry

CEV Replacement

- Necessary for upkeep of CEV for emergency situations
- Variable gravity testing
  - CEV replacement once before each gravity testing phase
- During Mars Mission Simulation, replacement of CEV will occur once a year

Construction Options

- Human EVA
- Robotic construction
- Combination of robotic and human EVA

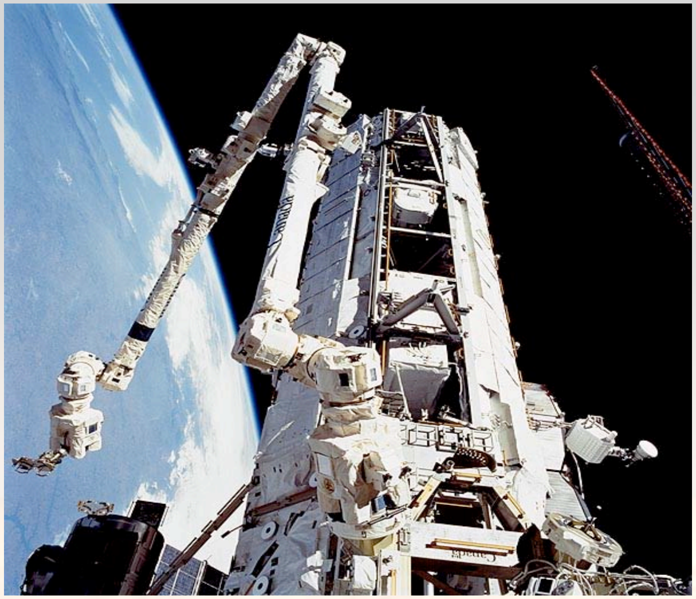


Image: http://iss.sfo.jaxa.jp/iss/5a_1/pict/s102e5166.jpg
Image:http://www.space.gc.ca/asc/img/apogee_1104_mbscanadarm2.jpg

Robotic Construction

Robotic assistance used in construction:

- Mobile Servicing System (MSS)
- European Robotic Arm
- Ranger TSX
- Robonaut

Mobile Servicing System

- Can only be used during 0g construction
- Consists of three main sub-systems:
  - Remote manipulator system (Canadarm2)
  - Dexterous manipulator
  - Base system

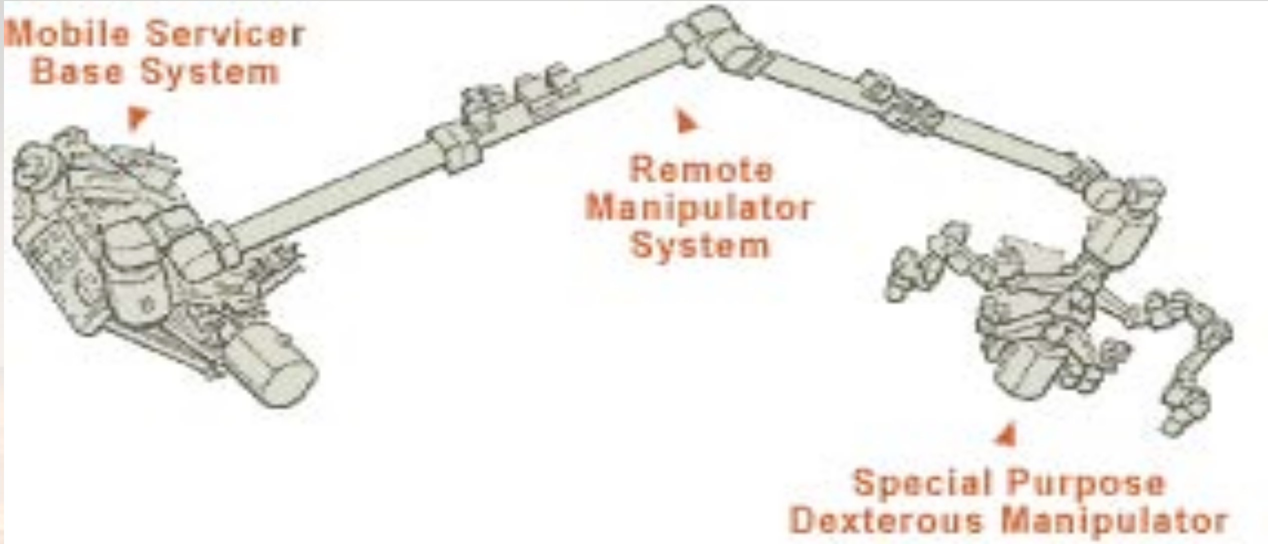


Image: http://spaceflight.nasa.gov/station/assembly/elements/mss/index.html

Mobile Servicing System

Canadarm2 (Remote Manipulator System)

- 7° range of motion
- Length: 17.6 m
- Mass handling capacity: 116,000 kg
- Peak operational power: 2,000 W
- Average power: 435 W
- Mass: 1,800 kg

Image: http://www.mdrobotics.ca/what_we_do/ssrms.htm

Mobile Servicing System

Image: http://en.wikipedia.org/wiki/Image:ISS_Canada_Hand.jpg

Dexterous manipulator

- 15° range of motion
- Length: 3.5 m
- Mass: 1,660 kg
- Peak Operational Power: 2,000 W
- Average Power: 600 W
- Capable of handling delicate assembly tasks

Mobile Servicing System

Base system

- Moves along rails on main trusses
- Holds the Remote Manipulator System
- Mass: 1,450 kg
- Peak operational power: 825 W
- Average power: 365 W
- Provides lateral mobility of MSS

Benefits of Using MSS

- Already in place on the main trusses
- Can be operated from inside the station
- Can move up to 116,000 kg
- Assists astronauts on EVA
- Can assist with docking at central node
- No extra development or launch costs

European Robotic Arm

- Will be launched in 2007 with Russian MLM
- Length: 11.3 m
- Reach: 9.7 m
- Mass: 630 kg
- Handling capacity: 8,000 kg
- Peak operational power: 800 W
- Average power: 475 W

Image: http://www.esa.int/esaHS/ESAQEI0VMOC_iss_0.html

European Robotic Arm

Image: http://www.answers.com/topic/european-robotic-arm

- Handling capacity much less than MSS
- Primarily for installing and deploying solar arrays
- General inspection of the station
- Supports astronauts in EVAs
- Only used in 0g construction
- No launch or design costs

Ranger TSX

- Currently at TRL greater than 3
- Robotic assistance may greatly reduce the time and number of EVAs
- Will need to be launched

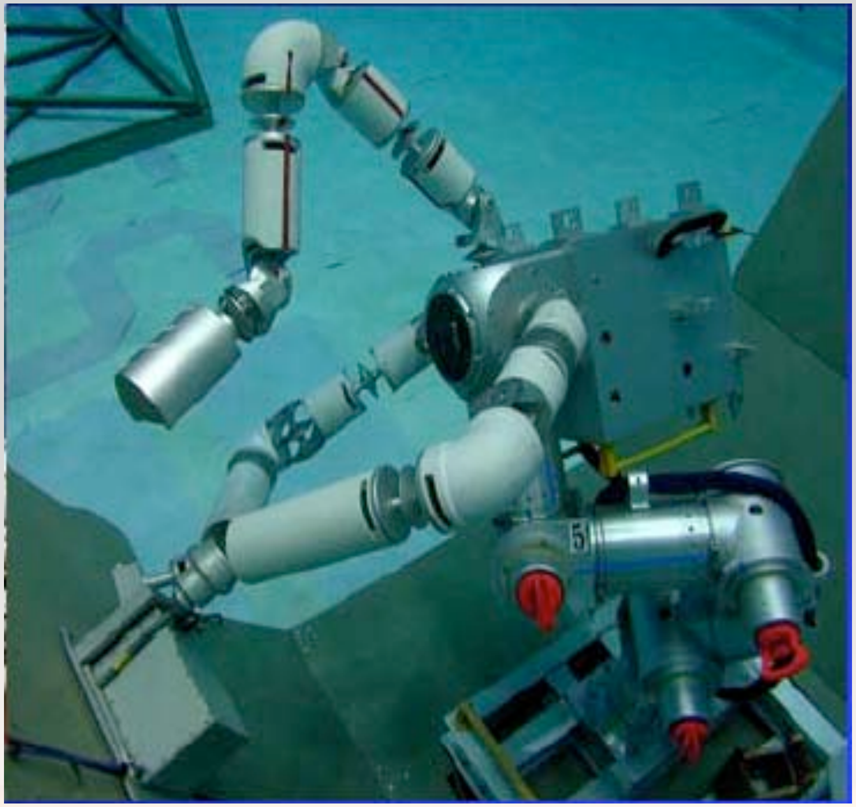


Image: http://www.icase.edu/workshops/hress01/presentations/akin.pdf

Robonaut

- Will work side-by-side with humans, or where risks are too great for humans
- Controlled by a telepresence control system (virtual reality)
- Designed to do EVA tasks robots usually cannot perform
- Looking into possible use of Robonauts to aid in construction/upkeep of SSP
- Also needs to be launched

Summary of Robotic Assembly

- Will be using Mobile Servicing System to construct the townhouses
- Using ERA to install solar arrays
- Looking into the use of robotic assistance (Ranger and Robonaut) to cut down on astronaut EVA duration and cost

Construction

- Converting ISS to SSP
  - Relocate 14 ISS modules
  - Install 10 new modules
  - Install transfer tubes and reinforcements
  - Install new propulsion / avionics packages
- Operations / EVA
  - 14 disconnections; 11 pressurized
  - 41 connections; 23 pressurized
  - 127 EVAs to complete conversion

Launch Vehicles

- **Manned:** Crew Launch Vehicle (CLV)
  - Exploration Systems Architecture Study (ESAS) Component
  - Will carry Crew Exploration Vehicle (CEV)
  - $300M per launch (*estimated*)
- **Cargo:** Boeing Delta IV Family
  - Five configurations to optimize expenses
  - 8,500 kg to 24,000 kg payload to ISS orbit
  - $133M to $254M per launch

Image: Exploration System Architecture Study. National Aeronautics and Space Administration. NASA-TM-2005-214062, November 2005
Image: Delta IV Payload Planners Guide. Boeing Corporation. MDC 00H0043, October 2000

Construction (cont.)

- **Objective:** Maintain station habitability during construction
  - Maximize EVA availability
  - Minimize CLV launches
- **Phase 1:** Build Townhouse A
  - Node 3A / RM only ISS modules relocated
  - Remaining modules must be launched
  - Habitable ISS volume remains usable

Construction (cont.)

- **Phase 2:** Build Townhouse B
  - Crew moves to SSP living quarters (TH-A)
  - Science modules from ISS can be moved
  - Node 3C is only newly launched module

- **Phase 3:** Reconfigure stability arms
  - Zvezda moved to opposite side of Node 1
  - Reinforcements frames installed
  - Zarya disconnected and de-orbited with trash

Construction (cont.)

Phase	Time (yrs)	Launches		EVAs	Objectives
		Crew	Cargo		
1	1.5	3	4	48	- Build Townhouse A
2	1.0	2	2	32	- Build Townhouse B
3	2.0	4	4	47	- Reconfigure Stability Arms - Install Reinforcements
Totals	**4.5**	**9**	**10**	**127**	

Construction requires fewer than 3 EVAs per month

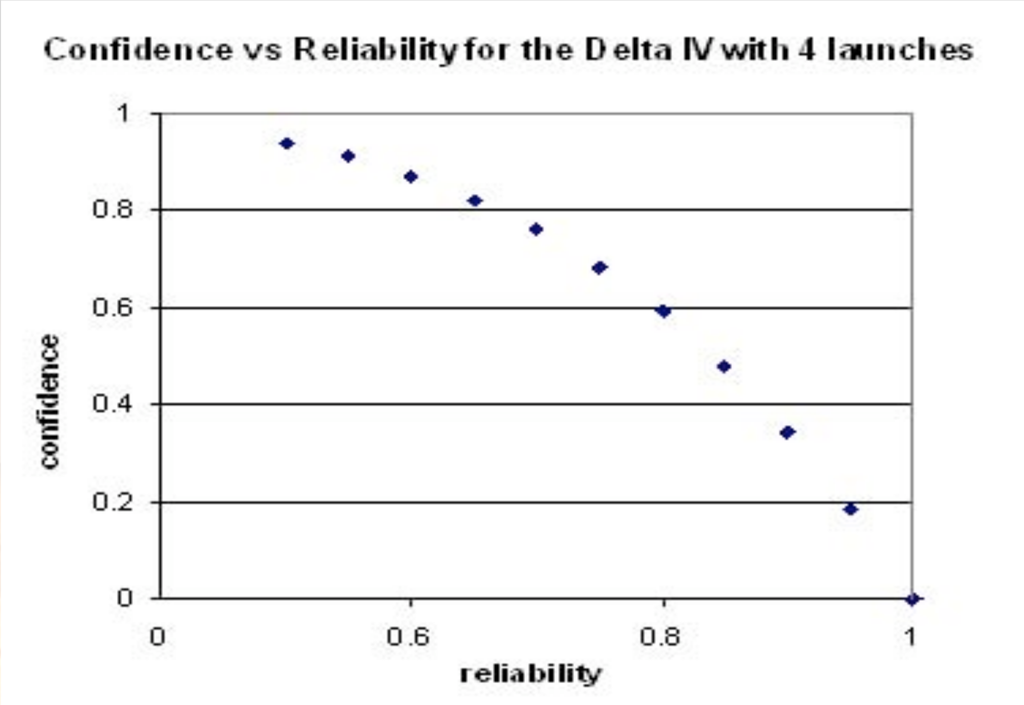
Cargo Launches

Vehicle	Launches	Payload (kg) Capacity	Payload (kg) Utilized	Cost ($M) Per Launch	Cost ($M) Total
Delta IV Medium	1	8,500	7,400	$ 133	$ 133
Delta IV Medium+ 5,2	2	20,500	14,900	$ 150	$ 300
Delta IV Medium+ 5,4	1	13,500	11,900	$ 160	$ 160
Delta IV Heavy	10	240,000	199,000	$ 254	$ 2,540
Total	**14**	**254,000**	**234,000**		**$ 3,133**

Cargo launches use **92%** of payload capacity

Reliability for launches

- There have been four launches of the Delta IV so far; all successful
- With only 4 launches they could claim 80% reliability with 60% confidence



Construction Propulsion

- Requirements
  - Small
  - Gimbaled
  - Restartable
- Several rockets considered: RL10A-4, RL10A-5, RS-72, SpaceX Kestrel
- SpaceX Kestrel chosen
  - LOX/Kerosene – clean burning
  - 31 kN thrust
  - Mass 75 Kg
  - I_{SP} 327
  - Sturdy construction
  - Capable of as many restarts as necessary
  - Thrust vector control

Image: www.spacex.com

Disposal of Remaining ISS Equipment

- Remaining equipment includes:
  - payload racks featuring out-of-date experiments and hardware not used in SSP
  - ISS solar arrays
  - Miscellaneous “junk”
- Solar arrays and radiators can be destroyed using small pushes to slightly lower orbits (either human or with robotic assistance)
  - Arrays are fragile and will burn up easily (low ballistic coefficient)
- Other equipment placed into or attached to Zarya (space dumpster) for containment during SSP construction and until de-orbit

Disposal of Remaining ISS Equipment

- Full Zarya
  - Mass: 19,300 kg
  - With all de-orbit material, total mass: 48,000 kg
- De-orbit Strategy: Based on Mir de-orbit
  - Attach primary thruster, use Zarya orbit maintenance motors and thruster gimbaling for attitude control
  - Burn to 165 km x 220 km altitude orbit
  - Burn to re-entry ellipse (with 83 km altitude perigee)
    - Dense Earth atmosphere drags parts to zero altitude
  - Total $\Delta V = 113$ m/s
  - Like Mir, aim for landing in unpopulated ocean area

De-orbiting Propulsion

- Requirements
  - Re-startable
  - Storable propellants
- Several Engines Considered:
  - RL-60, Aestus II, RL10A-4
  - Not all have storable propellants
- Aestus II Chosen
  - Propellant: N_2O_4/MMH
  - Rocketdyne/DaimlerChrysler joint venture
  - Developed as second stage for Ariane rocket

Image:http://cs.space.eads.net

Engine	Isp (s)	Thrust (kN)	Mass Propulsion (Kg)	Engines
Aestus II	378	60	2113	2
RL-60	465	289	2758	1
RL-10A-4	449	92.5	2116	2

Mass Distribution

Townhouse A

Module	**Mass (kg)**
Leonardo	5,580
Raffaello	5,500
Donatello	11,900
Cupola	1,880
Node 3A	15,500
Node 3B	15,500
PMA 3	1,200
Russian Research Module	14,500
Townhouse A Beams	2,500
Townhouse A Cable	30
Spin Up Package A	375
Batteries	3,300
Total	**77,800**

Mass Distribution

Townhouse B

Module	Mass (kg)
US Lab	14,500
Columbus	19,300
JEM-ELM PS	4,200
JEM-PM	15,900
Node 3C	15,500
Node 2	15,500
Townhouse B Beams	2,500
Townhouse B Cables	30
Spin Up Package B	375
Total	87,800

Mass Distribution

Central Axis

Module	**Mass (kg)**
Bearing/Motor Combination	600
P6 truss	15,900
S6 truss	15,900
CEV	23,000
PIRS	3,630
PMA 5	1,200
CEV Adapter 1	1,200
CEV Adapter 2	1,200
Node 1	15,300
Orbit Maintenance & Attitude 1	1,350
Orbit Maintenance & Attitude 2	16,500
Solar Panels	1,280
Total	**97,060**

Mass Distribution

Stability Arm

Module	Mass (kg)
PMA 1	1,200
PMA 2	1,200
PMA 4	1,200
MLM	20,300
Zvezda	19,050
US Airlock	5,900
ESP-2	7,080
Crew Tank Package	30,240
Stability Arm Support	100
Total	**86,270**

Mass Distribution

ISS Truss

Module	Mass (kg)
S0 truss	13,970
S1 truss	12,600
P1 truss	12,600
P3/4	15,900
S3/4	15,900
P5	12,600
S5	12,600
Inflatable	968
ESP-1	7,080
ESP-3	7,080
Express Pallets (5)	11,350
Mobile Servicing System & Canadarm2	6,700
Radiators	14,400
Total	**143,800**

Mass Distribution

Space Station Phoenix

Section	Mass (kg)
Townhouse A	77,800
Townhouse B	87,800
Central Axis	97,060
Stability Arm	86,270
Main Truss	143,800
Total	**493,000**

Reusing ISS hardware

Major Unused ISS Components

Module	**Mass (kg)**
Zarya	19,300
Z1 Truss segment	8,755
Port Photovoltaic Array	21,600
Starboard Photovoltaic Array	21,600
PIRS	3,630
Radiators	9,720
JEM-RMS Large Arm	370
JEM-RMS Small Fine Arm	75
JEM-Exposed Facility	13,000
JEM-Exposed Section	2,700
Total Unused ISS	**100,750**
Completed ISS	**456,000**
Reused ISS components	**360,000**
Percentage of ISS reused	**79%**

Mass Budget

Mass on orbit	359,000 kg
Mass to be designed	1,700 kg
Mass to be built	37,300 kg
Mass to be launched	254,000 kg
Maximum operational mass	493,000 kg
Minimum operational mass	452,000 kg

Cost Goals

- Total budget = $20B
  - 30% Margin = $6B cushion resulting in $14B total budget
- No more than $1B per year to spend after construction

Cost Allocations

- Research & Development
- Manufacturing
- Launch
- Ground Control
- De-orbit of unused ISS mass

Cost Formulas

$$C\,(\$M) = a\left[m_i\langle kg\rangle\right]^b$$

Spacecraft Type	Nonrecurring a	Nonrecurring b	1st Unit Production a	1st Unit Production b
Manned Spacecraft	20.64	0.55	0.6494	0.662
Unmanned Earth Orbital	3.93	0.55	0.4464	0.662
Support Structure	10	0.55	0.55	0.66
Scientific Instruments	2.102	0.5	0.2974	0.7

Table and Image: http://spacecraft.ssl.umd.edu/academics/483F05/483L07.costing/483L07.costing.2005.pdf

Research & Development Costs

- ($4M)·(Mass of New Design, unmanned part in kg)$^{0.55}$
  - CEV Docking Adapter
  - Non Spin Bearing/Motor
- No support or manned structures for research and development

Mass of New Design, unmanned			
	Mass (kg)	**$M**	**$B**
CEV Docking Adapter	1,200	*197.5*	*0.1975*
Non Spin Bearing/Motor	500	*122*	*0.122*
TOTALS	1,700	319.6	0.3196

Manufacturing Costs

- $(\$0.45)\cdot(\text{Mass of Manufactured, unmanned part in kg})^{0.66}\cdot(\text{Production \#})^{-0.2344}$
- $(\$0.55)\cdot(\text{Mass of Manufactured, support structure in kg})^{0.66}\cdot(\text{Production \#})^{-0.2344}$
- $(\$0.65)\cdot(\text{Mass of Manufactured, manned part in kg})^{0.66}\cdot(\text{Production \#})^{-0.2344}$
- $(\$0.2974)\cdot(\text{Mass of Manufactured, scientific instrument in kg})^{0.66}\cdot(\text{Production \#})^{-0.2344}$

Manufacturing Costs (cont.)

Mass of manufactured, unmanned	Production #:	1	2	TOTAL
	Mass (kg)	$M		
CEV Docking Adapter	1,200	48.5		48.5
Non Spin Bearing/Motor	500	27.2		27.2
Xenon Tank 1	23	3.56	3.03	6.59
Xenon Tank 2	1,735	61.8		61.8
Xenon Tank 3	150	12.3	10.4	22.7
Bearing (inertial cap)	500	27.2	23.1	50.3
Motor (inertial cap)	500	27.2	23.1	50.3
	Total ($B)	0.208	0.0597	**0.267**

Manufacturing Costs (cont.)

Mass of manufactured, support structure	**Production #:**	1	2	**TOTAL**
	Mass (kg)	**$M**		
Transfer Tube	896	48.9	41.5	90.4
Module support structure A	2,500	96.2		96.2
Module support structure B	2,500	96.2		96.2
	Total ($B)	0.241	0.0415	**0.283**

Manufacturing Costs (cont.)

Mass of manufactured, manned	**Production #:**	1	2	**TOTAL**
	Mass (kg)	**$M**		
Node 3	15,000	370.8	315.2	685
Pirs (replacement)	3,630	145.4		145.4
	Total ($B)	0.516	0.315	**0.831**

Manufacturing Costs (cont.)

Mass of manufactured, scientific instruments	**Production #:**	1	2	3	4	5	6	7	8	**TOTAL**
	Mass (kg)	**$M**								
Solar Panels	650	27.7	23.5							51.2
Batteries	3,330	86.9								86.9
Canadarm 2	1,650	53.2								53.2
Photo-voltaic Radiators	1,220	43.1	36.6	33.3	31.1	29.5	28.3	27.3	26.4	255.6
Waste Collection Machine	111.5	8.06	6.85							14.91
Heat Rejection System Radiators	1,220	43.1	36.6	33.3	31.1	29.5	28.3			201.9
	Total ($B)	0.262	0.104	0.0665	0.0622	0.0590	0.0565	0.0273	0.0264	**0.663**

Launch Costs

- CLV / CEV launch = $300M
  13 Launches = $3.90B
- Delta IV Heavy launch = $254M
  11 Launches = $2.79B
- Delta IV Medium + 5, 4 = $160M
  1 Launch = $0.160B
- Delta IV Medium + 5, 2 = $150M
  2 Launches = $0.300B
- Delta IV Medium = $133M
  1 Launch = $0.133B
- 27 total launches = **$7.033B**

Ground Control Costs

- Total Cost = ($541M per yr)·(# yrs of project)
- Total Cost for 10 years = **$5.41B**

De-Orbiting ISS Mass Costs

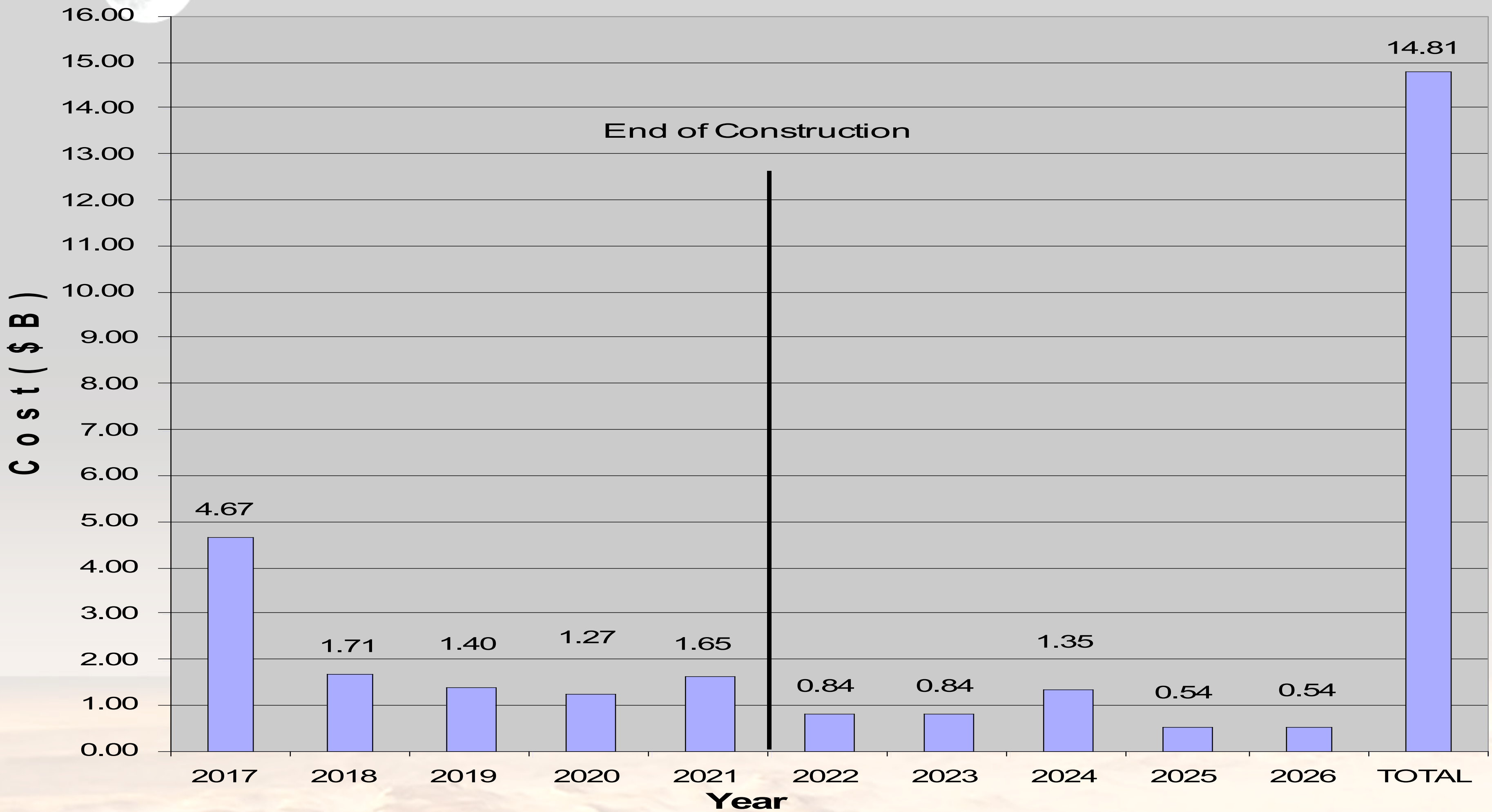
- Accounted for with launch of other materials and in launch schedule
  - Payload consists of rocket boosters and propellant for de-orbiting remaining ISS mass

- Total cost included in total launch cost

Summation of Budget

- Total Cost for SSP
  $14.8B
- Amount over 30% Margin Goal
  $0.80B
- Amount under Level 1 Requirement
  $5.20B
- Resulting Margin
  26.0%

Year by Year Costs



Cost Discounting

Year	$B 2006	NPV	NFV
2017	4.67	1.80	12.11
2018	1.71	0.60	4.88
2019	1.40	0.45	4.39
2020	1.27	0.37	4.38
2021	1.65	0.43	6.27
2022	0.84	0.20	3.51
2023	0.84	0.18	3.86
2024	1.35	0.27	6.82
2025	0.54	0.10	3.00
2026	0.54	0.09	3.30
Total	**14.81**	**4.48**	**52.53**

*Constant Discount Rate (r) = 0.1

Worst Case Scenario

- Based on reliability of our launch vehicles, 2 unsuccessful launches is the worst possibility
  - Worst case is two launches both carrying manufactured Node 3s
- To manufacture and launch again is additional $1.07B
  - Resulting Total Cost = $15.87B
  - Resulting Margin = 21%

Problems with Cost

- Over our goal budget of $14B
  - Still under $20B requirement, but wanted to meet our 30% margin goal
- Over $1B budgeted for 2024
  - Due to number of launches in that year

Solutions to Cost

- Find cheaper launch costs
  - Cheaper launch vehicles
  - "Perfect Packing" at $10,000 per kg results in a total project cost of **$13.98B**
- Gravity testing could be shortened from 10 months to 6 months per test
- 4 months of unused time at end of mission
- Spread launches out for year 2024
  - Lower cost in 2024 while meeting less than $1B per year requirement

Summary

- Rotating station made up primarily of reused ISS components
- Should cost less than $20B
- Gravity variable between 0 and 1g
- Capable of Mars simulations and extensive fractional gravity research
- Can support six people for three years without re-supply

Conclusion

- Configuration satisfies volume needs
- Radiation study accomplished without risking astronauts or going over budget
- Significant science on orbit
- Variable gravity environment
- Full attitude control for specified orientation
- Design is stable within bounds of error

Main Goals

- Manned Mars mission simulation
- Variable gravity testing
- Scientific studies on human physiology
- Cost effective design
- Utilize ISS components

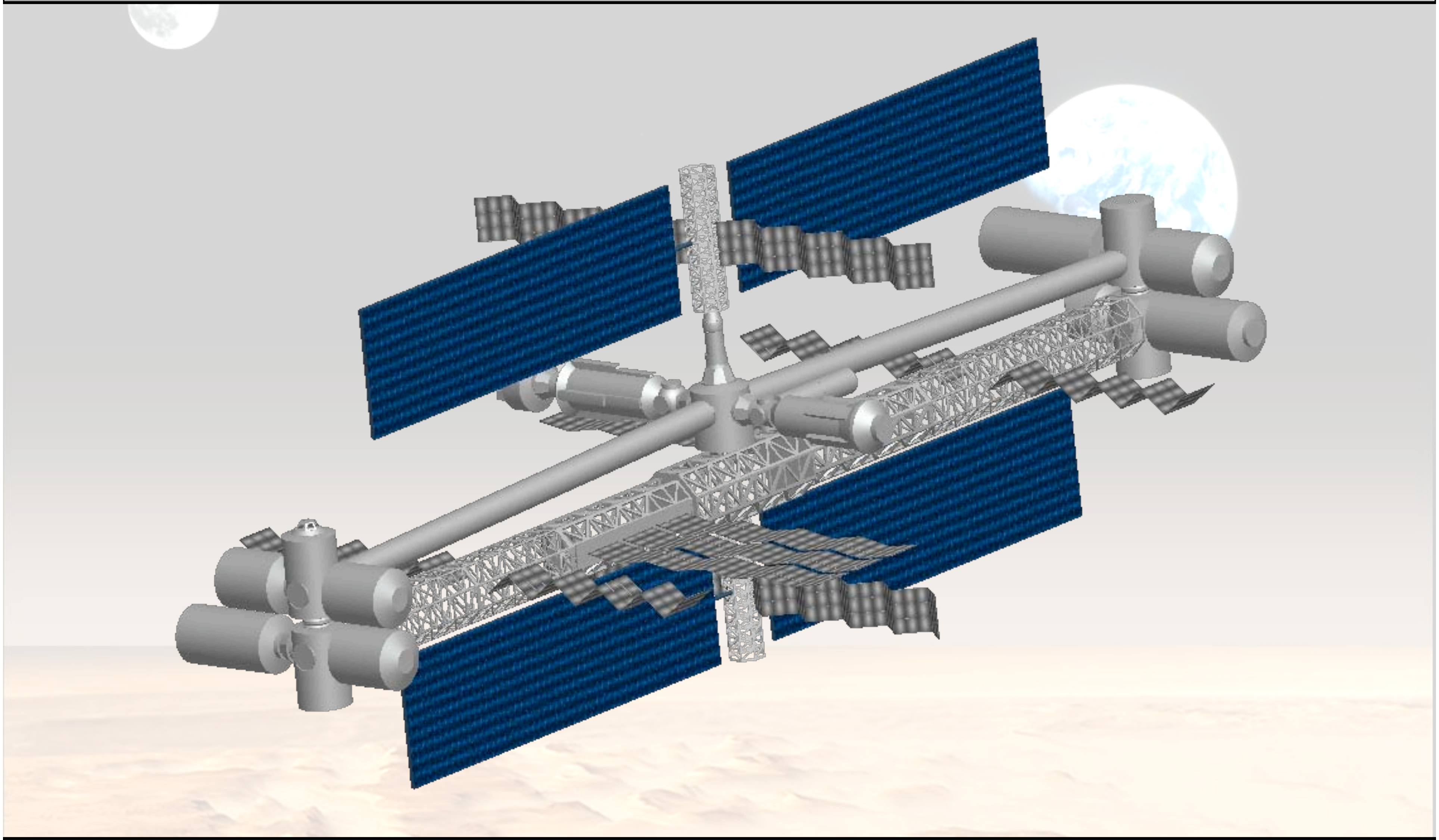
Difficulties

- Station configuration and stabilization
- Radiation protection
- Human living space requirement for six people for three years
- Consumables to supply a six person three year mission

Achievements

- Stable station configuration
- Attached radiation mission with ideal station location for construction
- Using 360,000 kg (79%) of ISS
- Recovering $36B of $100B invested in ISS
- Total cost of $14.8B
- Full attitude control and orbit maintenance capabilities

Conclusion



Driving Force

"We do not know where this journey will end, yet we know this -- human beings are headed into the cosmos. Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across the open sea. We choose to explore space because doing so improves our lives and lifts our national spirit"

– George Bush