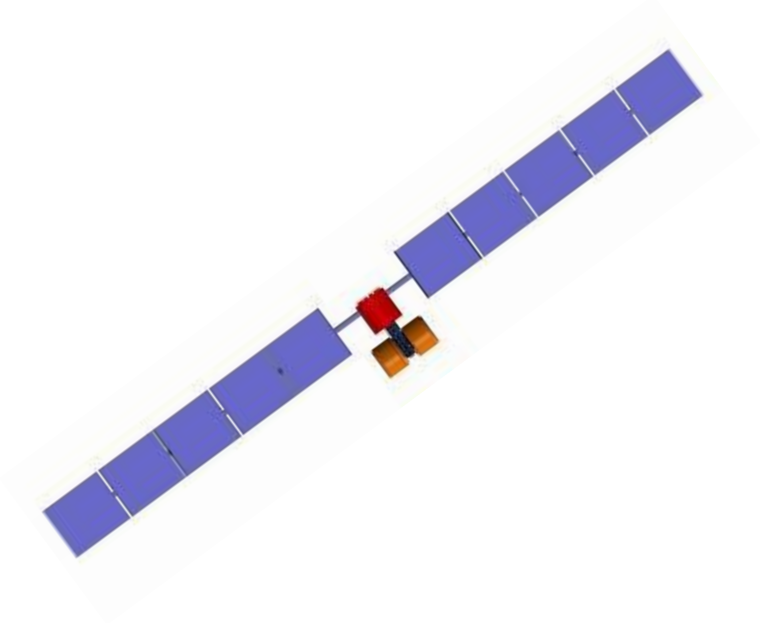
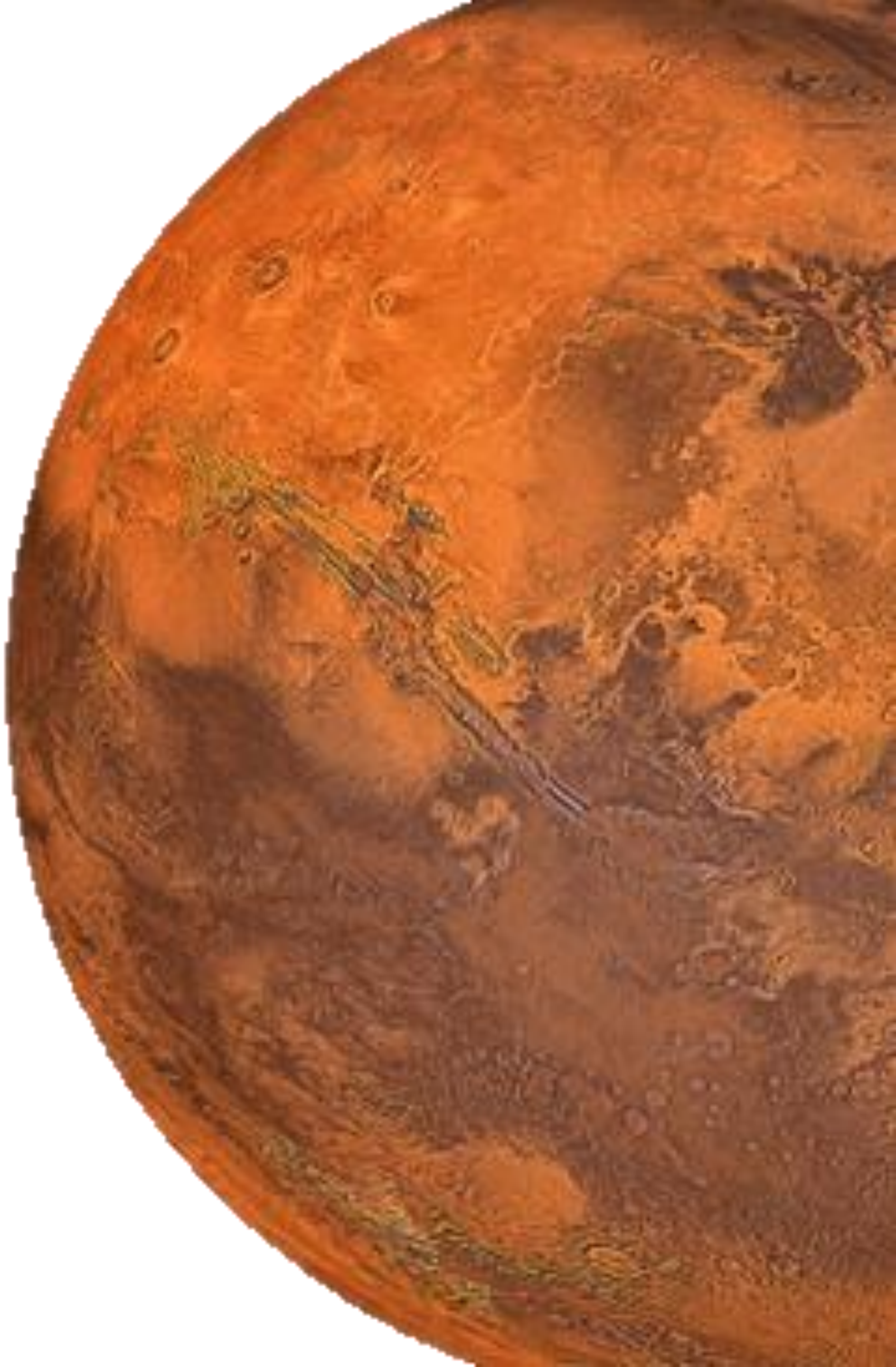




RASC-AL Final Review

Team Lead: Carmon Chord

Team: Daniel Dominksi, Timothy Emerson, Mykale
Holland, Brandon Jost, Brandon Whitney, and
Jacob Wilmoth

May 2, 2018

RASC-AL Competition

- NASA RASC-AL Theme 2 – Artificial Gravity Reusable Crewed Deep Space Transport
- Develop a vehicle which is capable of simulating Mars' gravity for a majority of the mission to and from Mars
    - ~1,100 day conjunction class mission
    - Launch from cis-lunar orbit and travel to 5 sol Martian orbit
- Use a hybrid propulsion system
    - High thrust chemical system
    - Low thrust electric system
- Determine additional budget authority needed
- Technology ready for deployment and operations by 2029

RASC-AL Deliverables

- Abstract (January 21)
  - Paper describing proposed concept
  - Video to show concept in action
  - OSU was chosen as one of the 7 teams to continue to semi-finals
- Mid-Project Review (April 1)
  - Paper delves into the development and engineering analysis for the concept
  - OSU was not chosen to move to the final round
- Final Technical Paper
  - In-depth review of the final concept and supporting analysis

Major Requirements

- Preserve life
- Mass Limit – 50 metric tons
- Use no more than 750 kW BOL solar arrays
- Simulate Mars' gravity level a majority of the mission
- Thrusters used for rotation need to be fuel efficient
- System must be capable of withstanding the environment of space for at least 15 years
- Capable of supporting at least 3 roundtrip missions to Mars
- Determine additional budget authority needed for mission

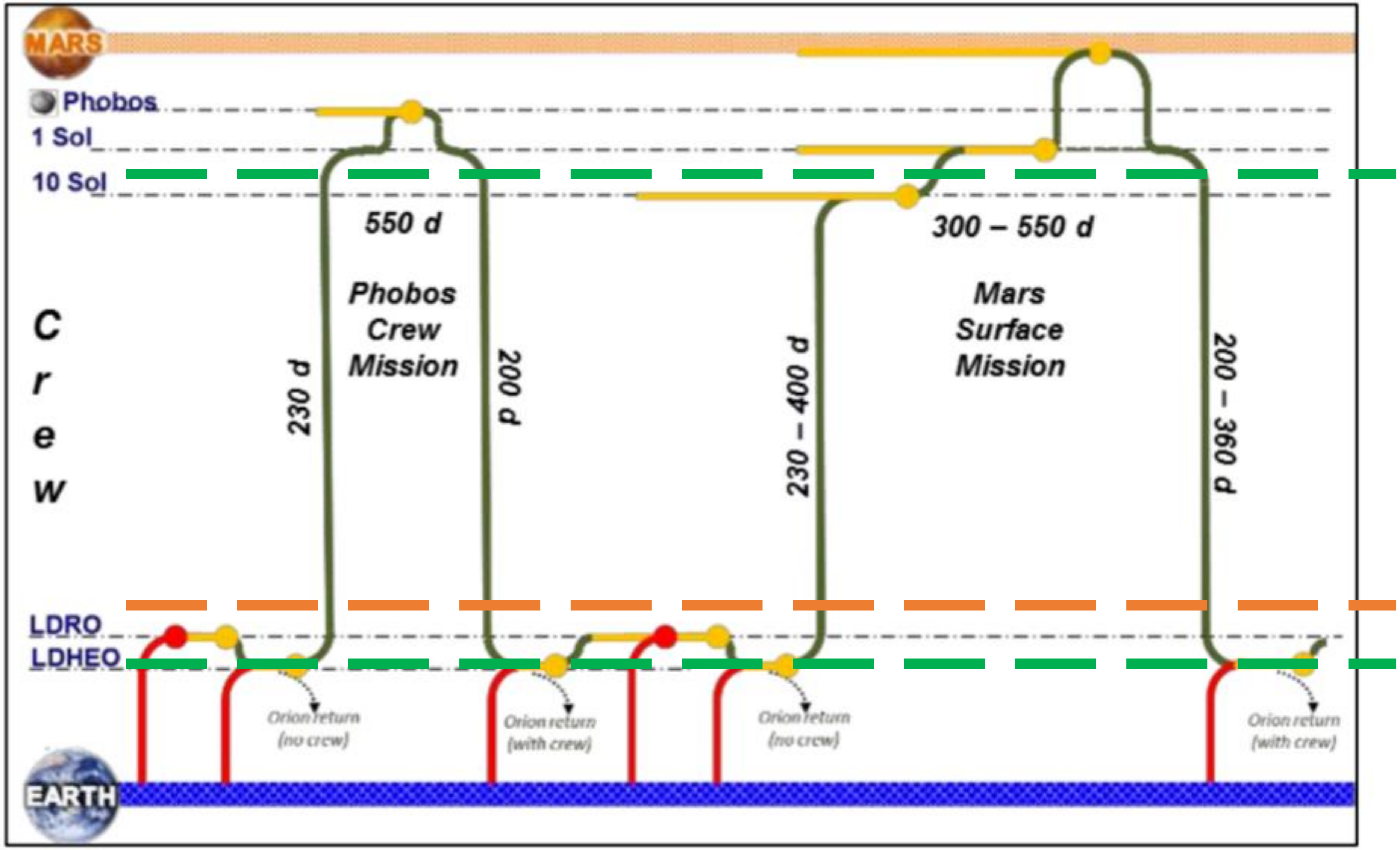
Assumed Requirements

- Artificial gravity must be created through rotation
    - No new advancements in physics
- Expandable shaft must withstand rotation
    - No gravity without rotation
- Additional bracing in expandable shaft will be necessary
    - Supports by themselves would twist around one another
- Astronaut must be capable of moving between pods via the expandable shaft
    - Contingency plan
- Expandable shaft and pods cannot crash into solar arrays
    - Total destruction of spacecraft

Major Design Drivers

- Mass Limit
  - Must stay below 50 metric ton limit placed by propulsion system
  - Conflicted with every component of the design
    - Time to Full Rotation Speed
    - Robotic Systems
    - Central Hub Design
    - Thickness of Shroud
- Power Usage
  - System must be able to operate when solar arrays degrade from 750 kW beginning of life to 607 kW end of life
  - Limited NASA Power Data
  - Impacted the rotational thrusters and spin up time

RASC-AL CONOPS



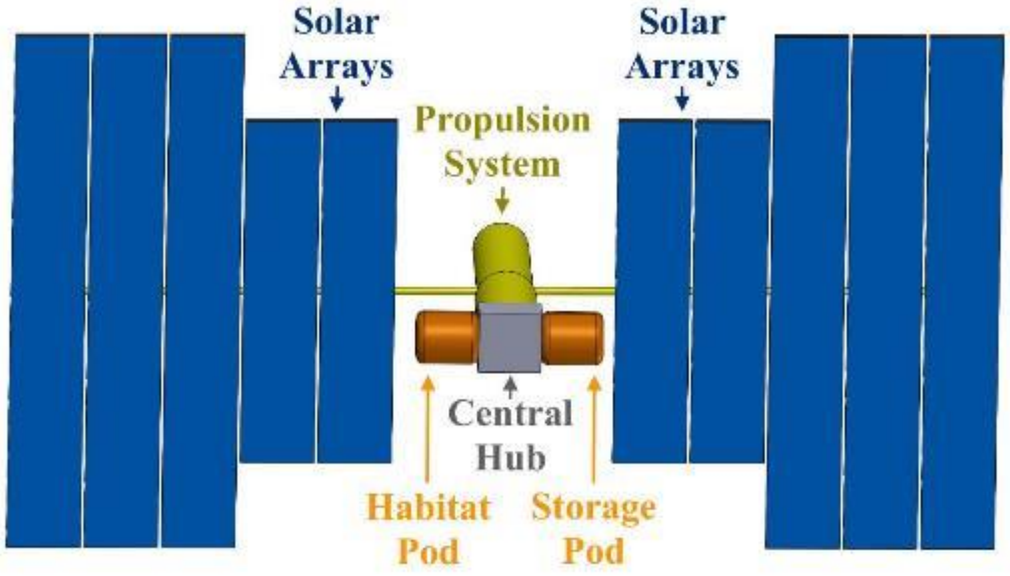
Chemical Thrust (890N)

Electric Thrust (8.75N)

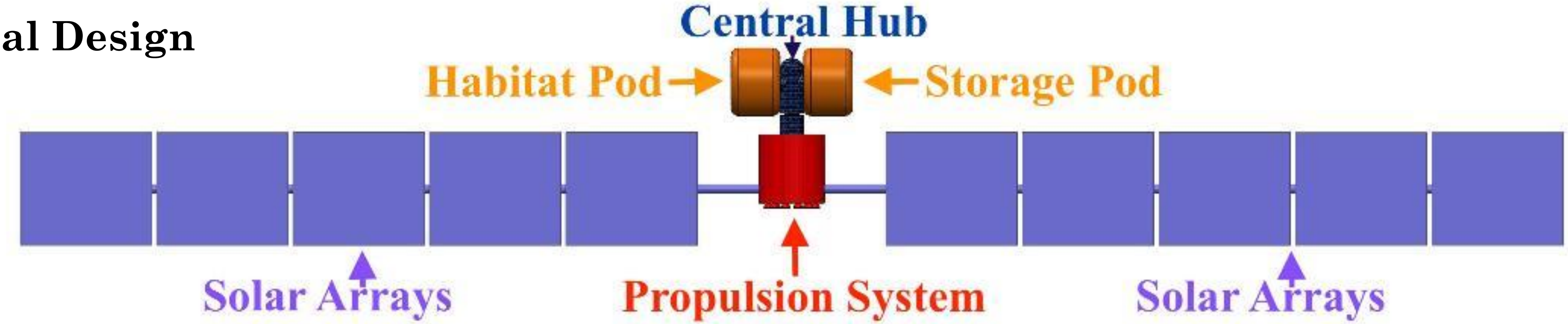
Chemical Thrust (890N)

Design Evolution - Hammerhead

Initial Design

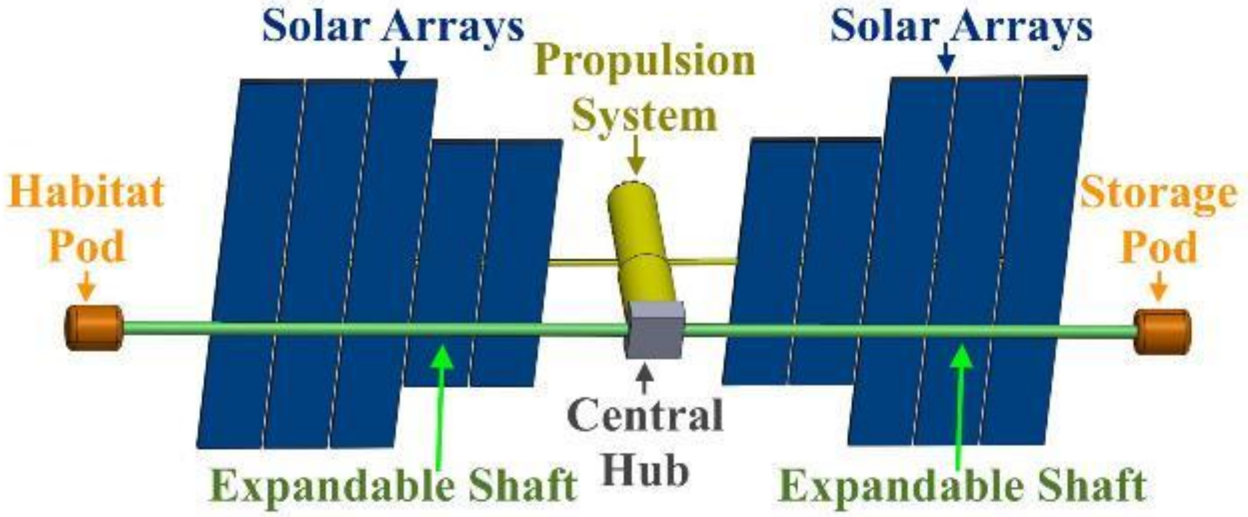


Final Design

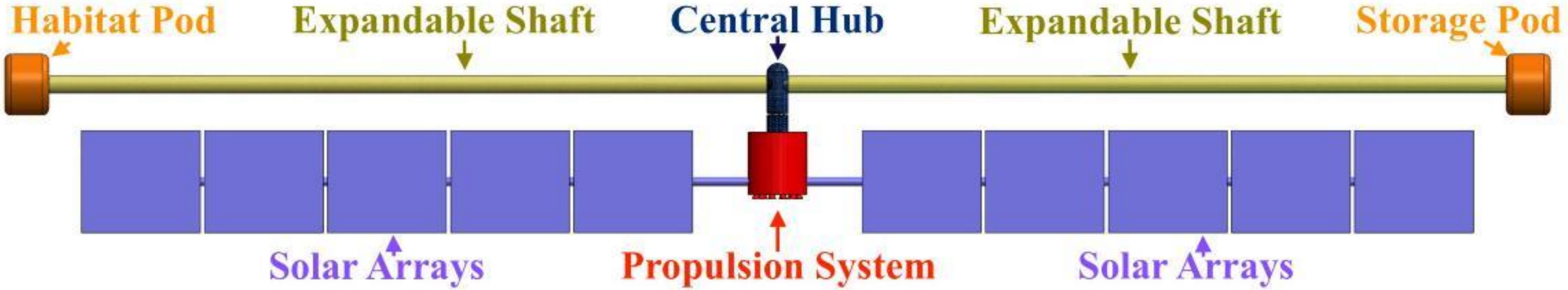


Design Evolution - Transit

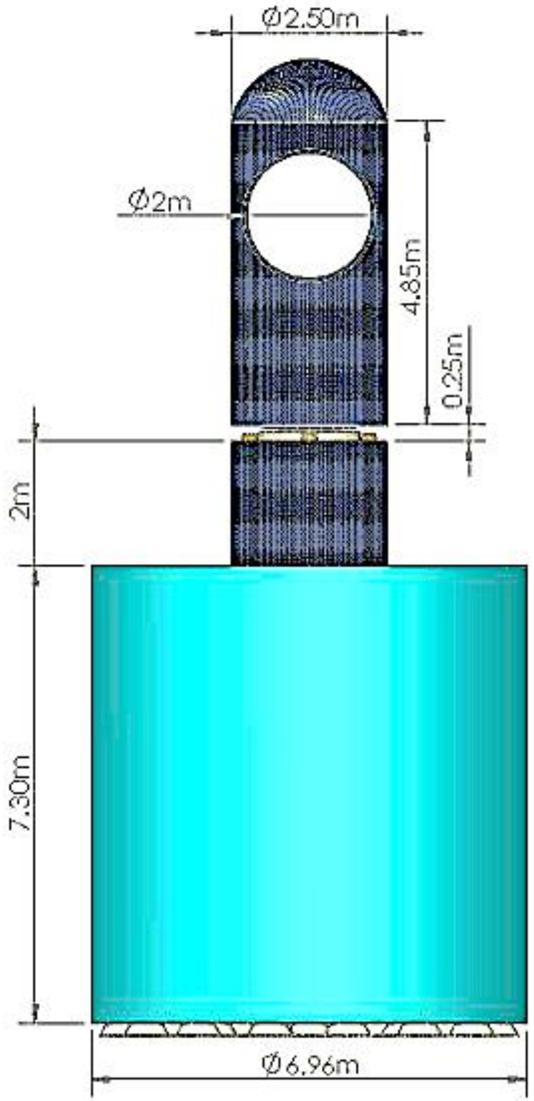
Initial Design

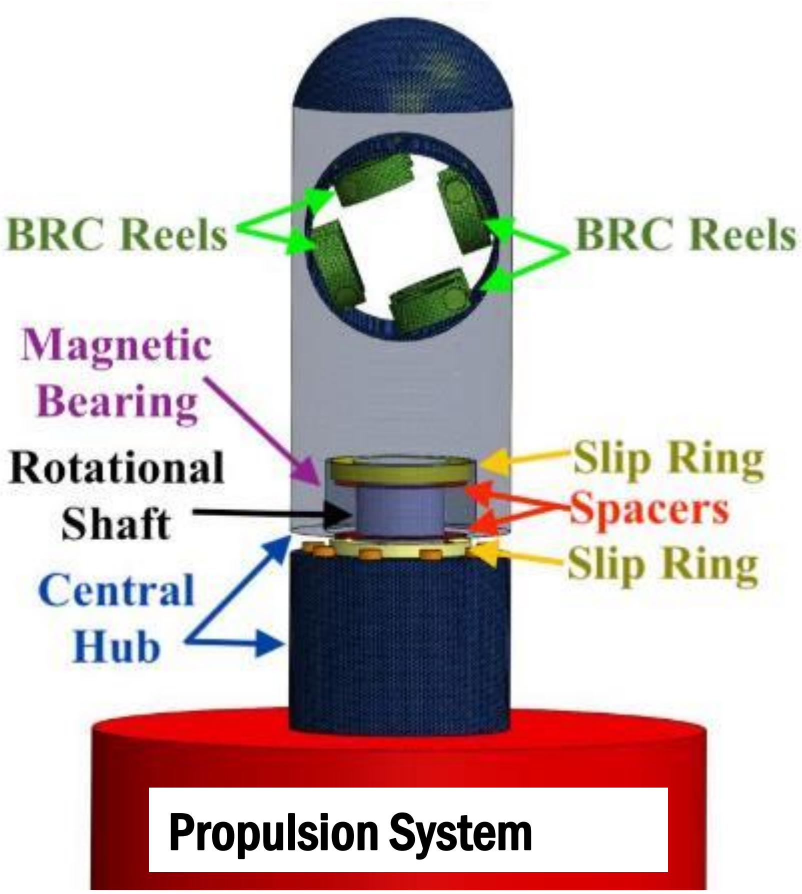


Final Design



Central Hub





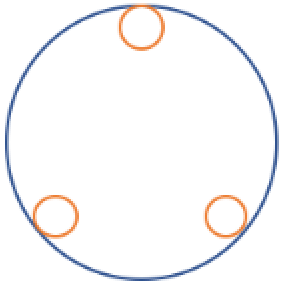
	Magnetic Bearing
Material	Neodymium Magnetic
Friction	Minimal
Lubrication	None
Possible Issue	Degradation issue with magnetism due to radiation
Maintenance During Mission	None
Size	1 meter
Cost	Expensive
Technological Readiness	9

System Loads

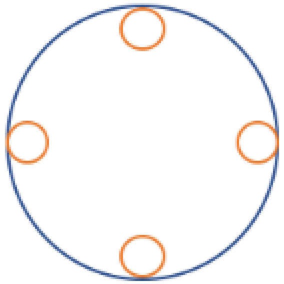
- **Worst Case Loads Scenario:** Launch in Transit Configuration
  - 17x increase in bending stress over launching in hammerhead configuration
  - Safer to launch in hammerhead configuration and transition to transit configuration during electric thrust
    - Bending Stress for Electric Thrust – Transit Configuration: 0.031 MPa

Chemical Thrust – Transit Configuration, No Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	196.5 (Compression)
Moment (Nm)	1.66×10^{4}
Bending Stress (MPa)	2.71

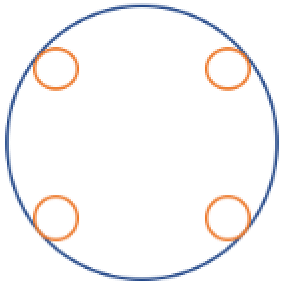
Expandable Shaft Orientations



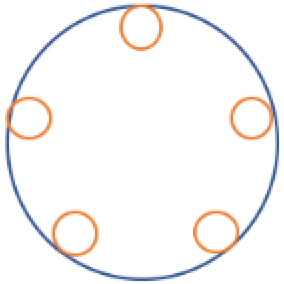
Triangular Orientation



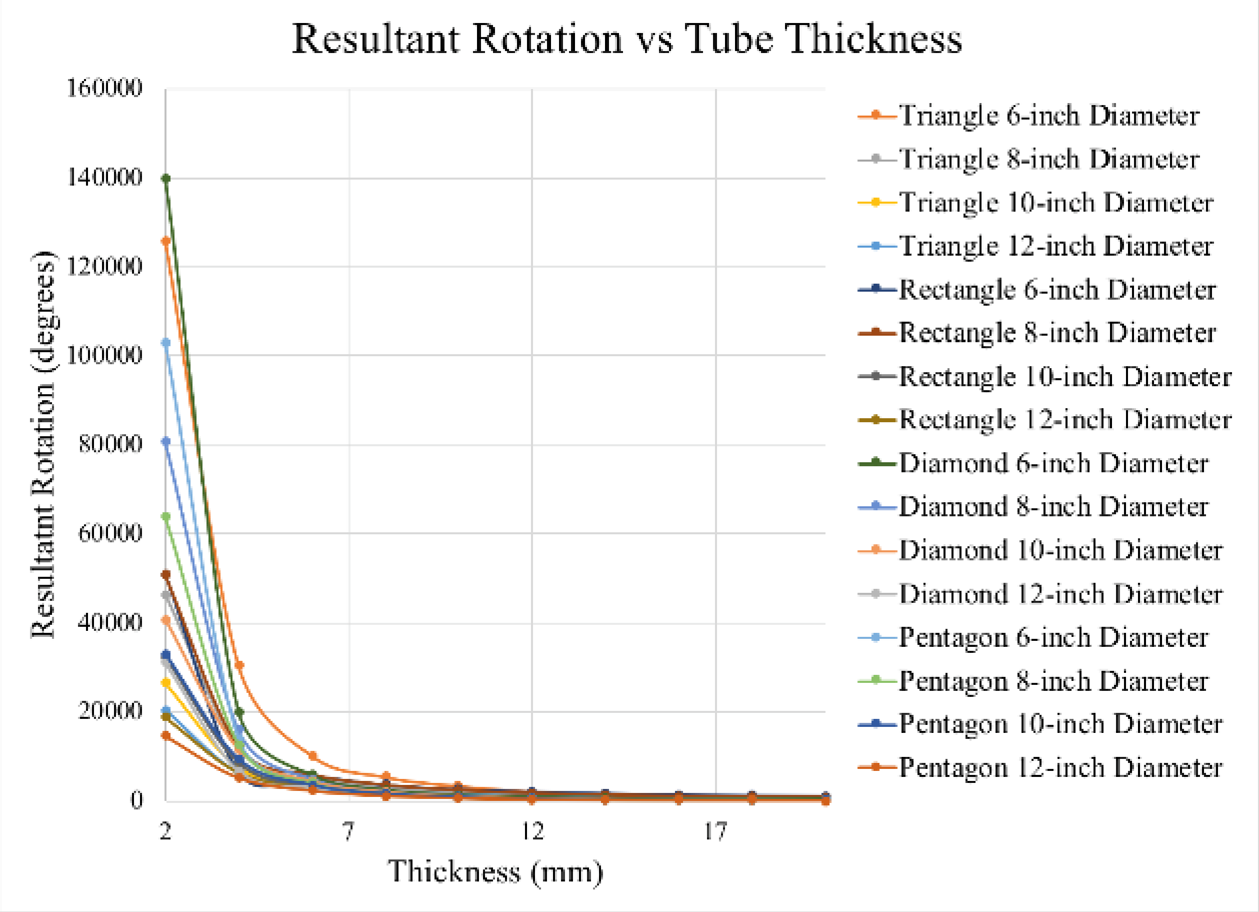
Diamond Orientation



Rectangular Orientation



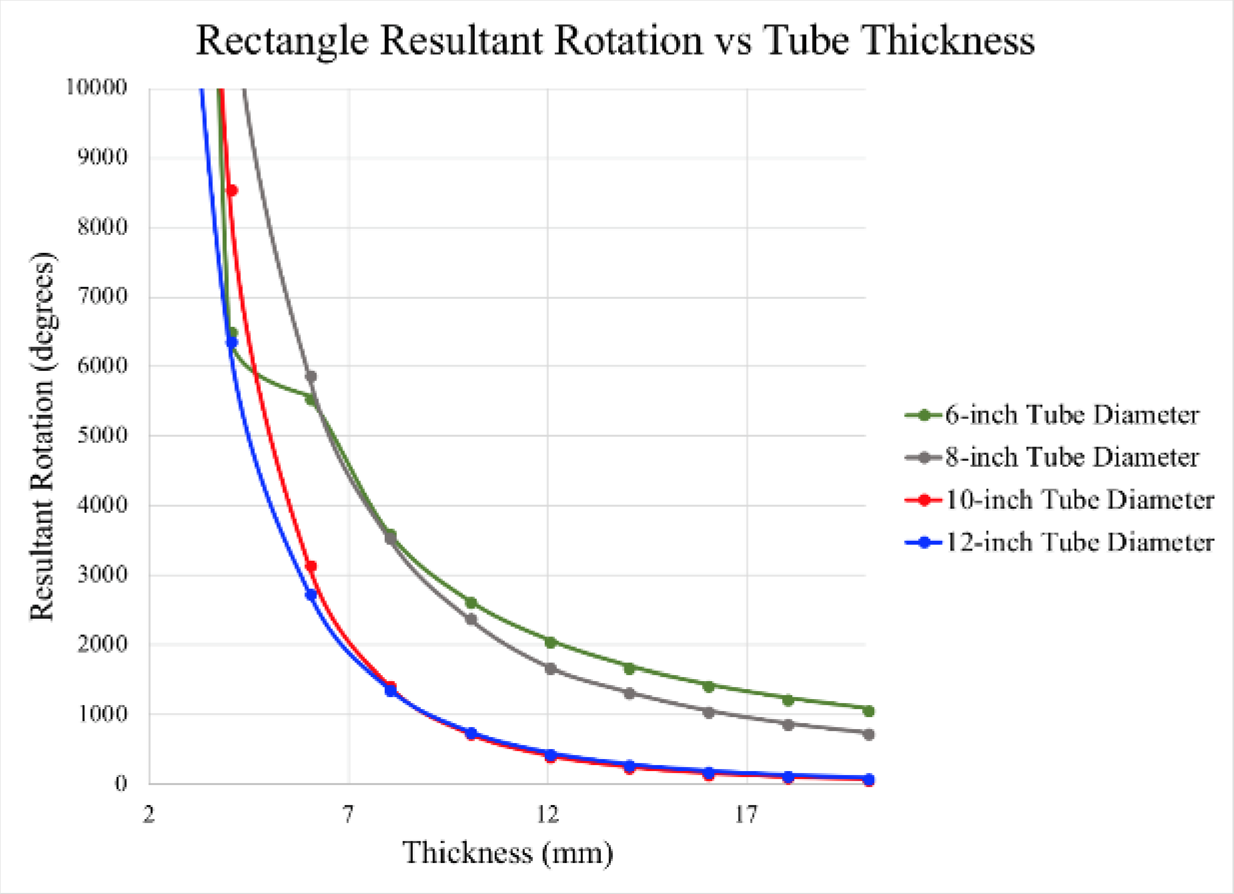
Pentagon Orientation

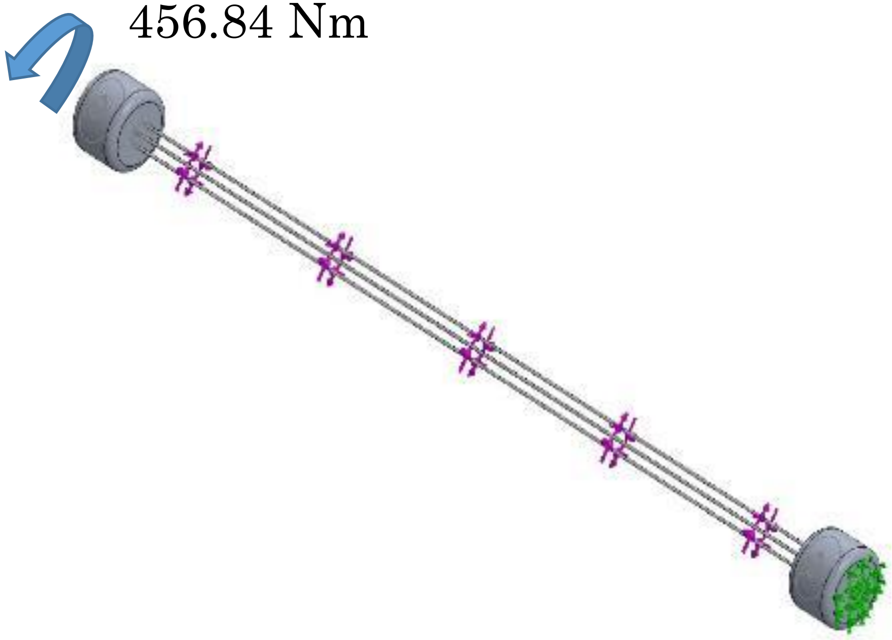


Chosen Design: Rectangular
Reason: Pentagon required more mass for minimal decrease in resultant rotation making rectangular the better choice

*All orientations eventually converge

Expandable Shaft - Rectangular





Total Torque:
456.84 Nm

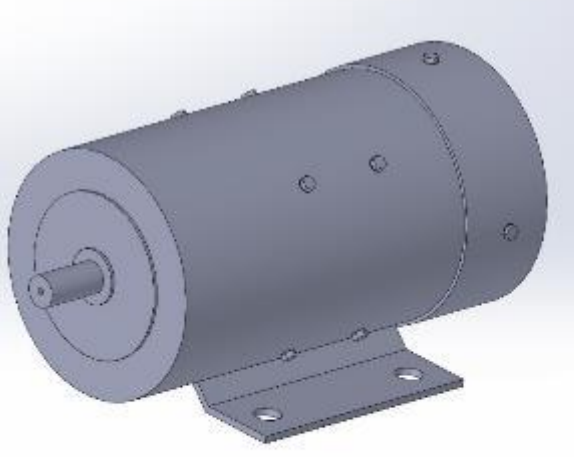
Fixed End

Chosen BRC Dimensions:
10-inch Tube Diameter
14-millimeter Tube Thickness

Resultant Rotation:
271 degrees

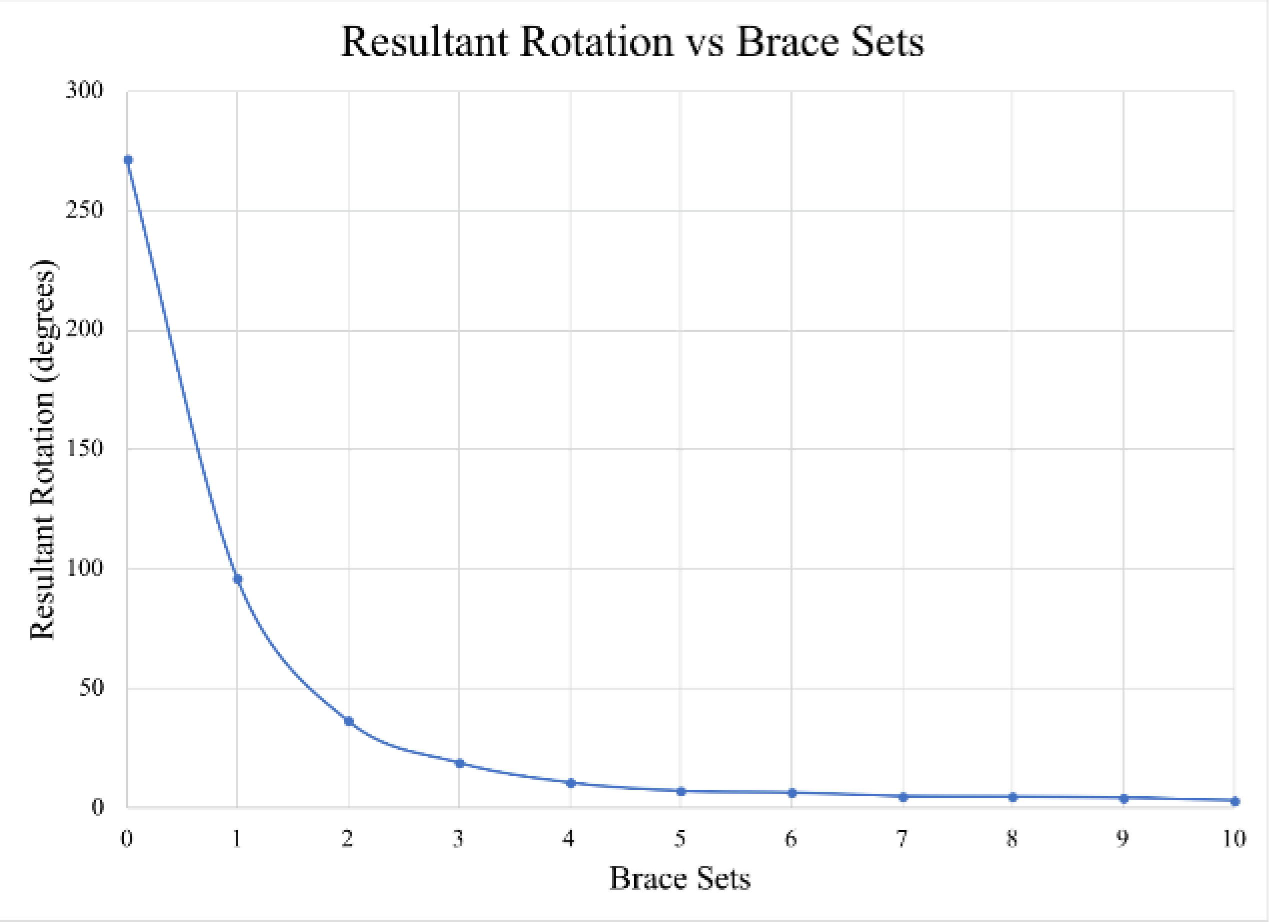
BRC Expansion/Contraction Motor

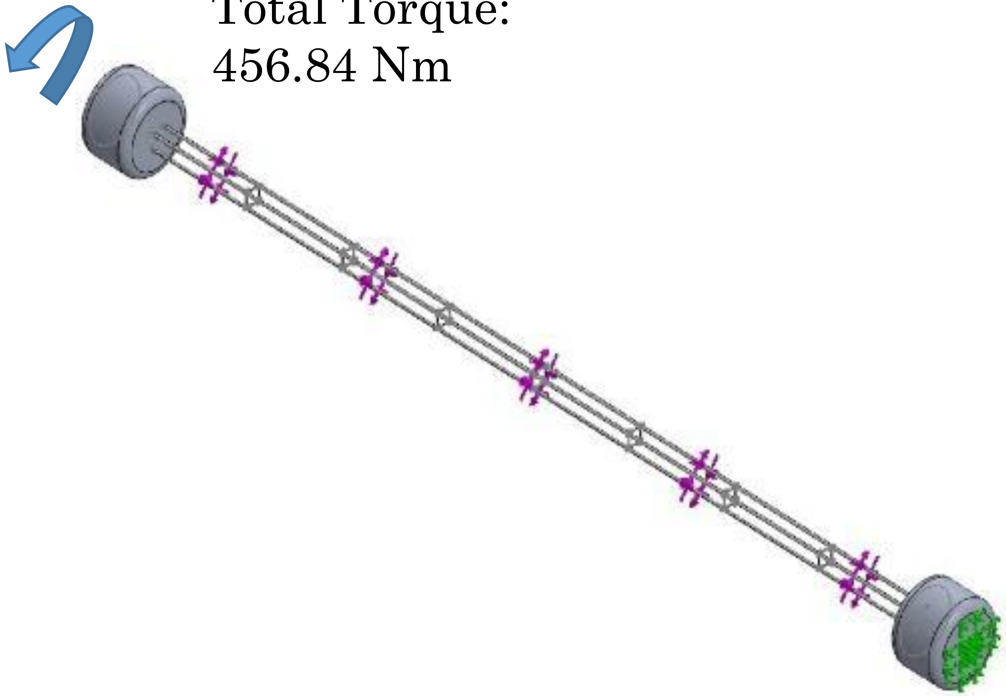
- A motor will be necessary to control the expansion and contraction of the BRC supports
  - During the expansion of the BRC, the supports will need to be slowed down to prevent damage to the system
  - During the contraction of the BRC, the supports will need help reel in
- Expansion and Contraction Time:
  20 minutes



Ohio Electric Brushless Motor

Additional Bracing FEA





Total Torque:
456.84 Nm

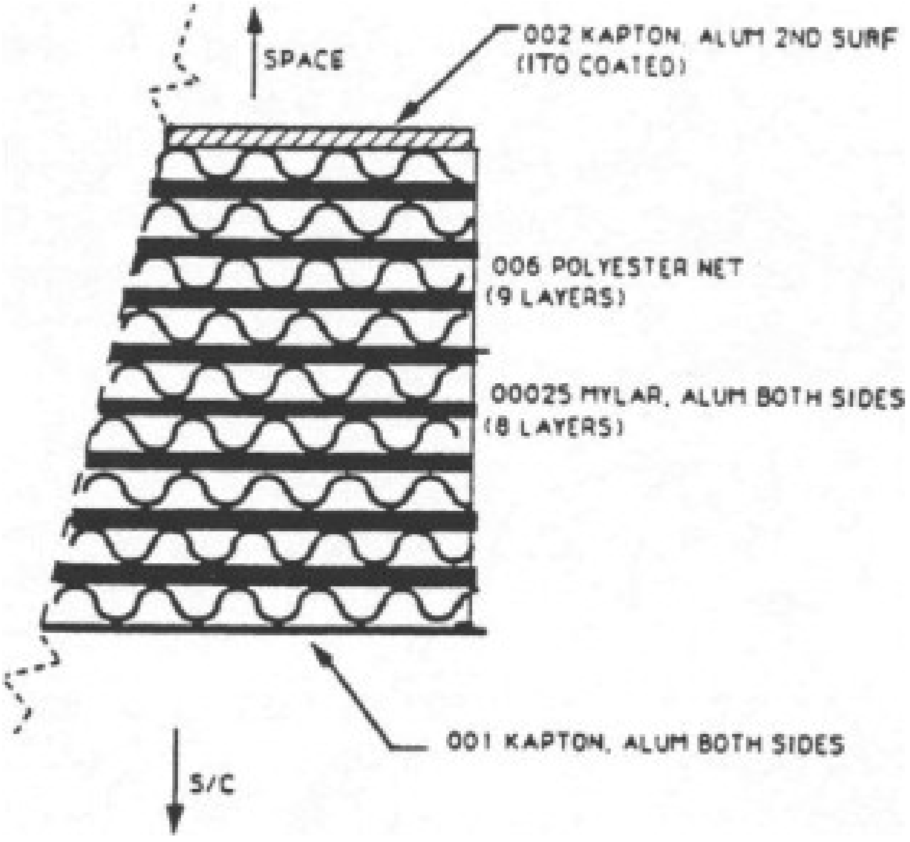
Fixed End

Nominal Brace Dimensions:
4-inch Tube Diameter
6-millimeter Tube Thickness

Chosen Number of Brace Sets: 7
Resultant Rotation: 1.99 degrees

Shroud Layup

- Shroud Layers (Outside to Inside):
  - Aluminized Beta Cloth (0.2 mm)
  - Aluminized Kapton (0.0076 mm)
  - Mylar (0.0051mm)
  - Nomex Netting (0.16 mm)
  - Kevlar (2 mm)
- Beta cloth, Kapton, and Mylar will allow the shroud to reject 90-99% of the sun's radiation
- Nomex netting will be layer between the reflective layers and Kevlar to minimize conduction effects
- Kevlar will protect the interior of the shroud and add strength to the structure

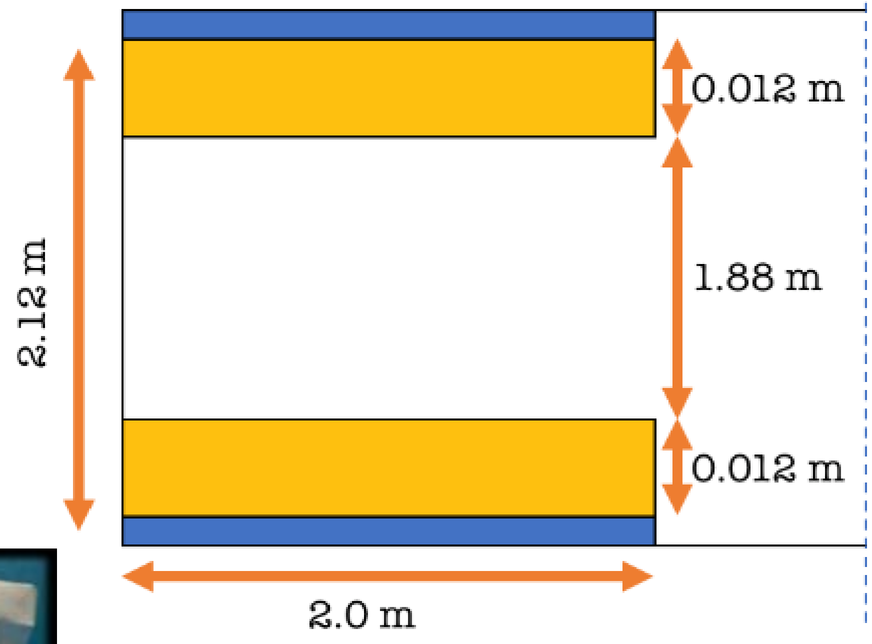


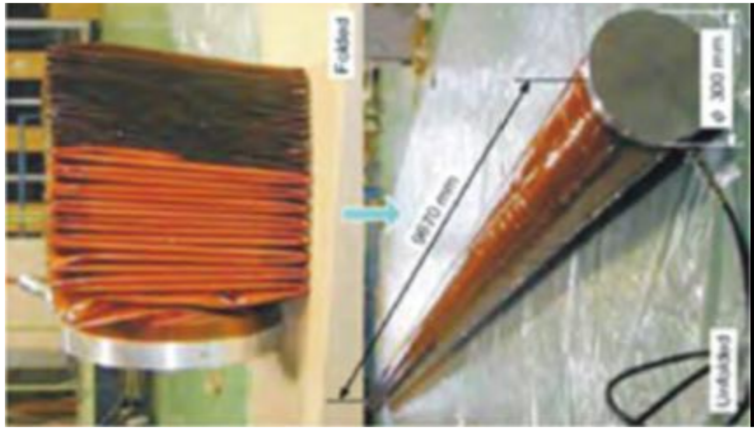
Layup Example

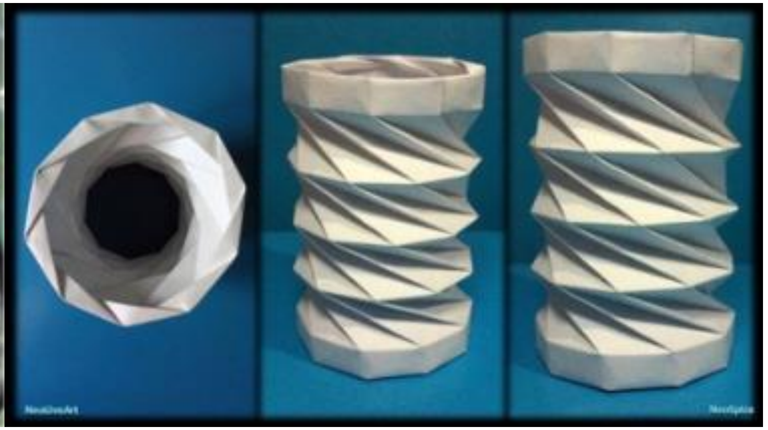
Shroud Origami

- Origami folding technique will allow the shroud to compress for hammerhead configuration
- Prefabricated fractal folds will allow the material to safely expand/contract without fatigue issues
- Allows the shroud to compact down to 2 meters

Central Hub Cross Section: Stored Shroud

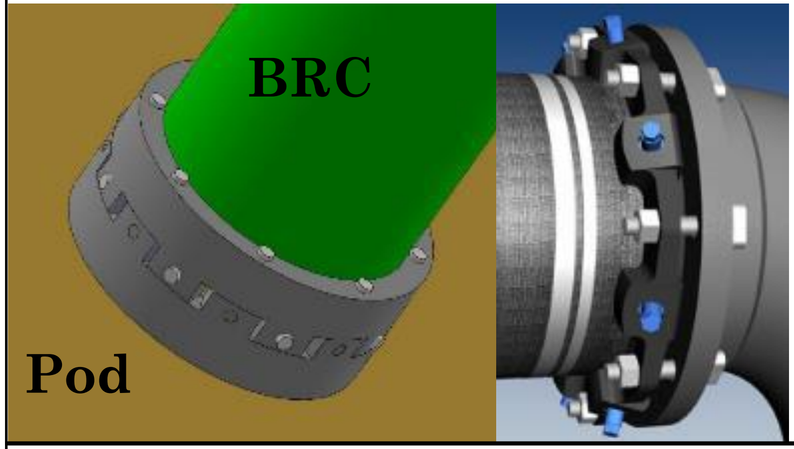






System Connections

BRC Supports and Pods Connection

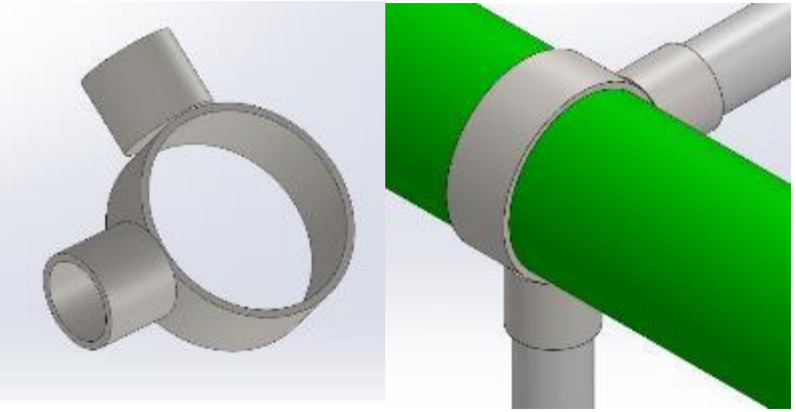


- Connector on both BRC and Pods
- Bolted to lock into place like a mechanical joint

Shroud and BRC Supports Connection

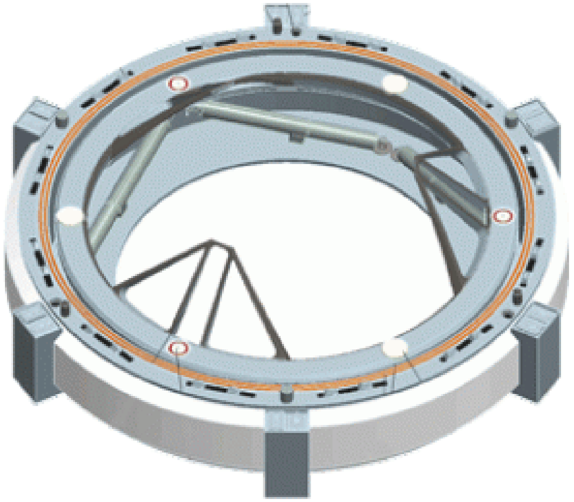
- Velcro will be wrapped around the supports by the robotic system and secured to the shroud’s Velcro patch

BRC Supports and Brace Connection



- Connections installed during construction
- Robotic system will position them when in transit configuration

Shroud and Pods/Hub Connection

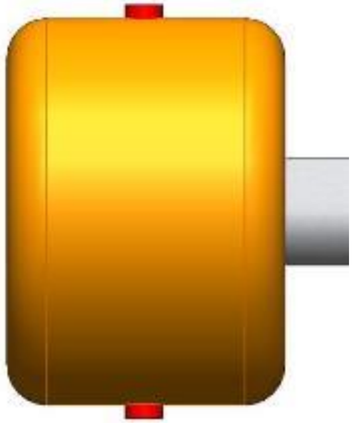


- Similar to NASA berthing mechanism
- Main connector will be bolted onto the pods/hub
- Shroud will have a smaller connector that will hook onto the main connection

Rotation

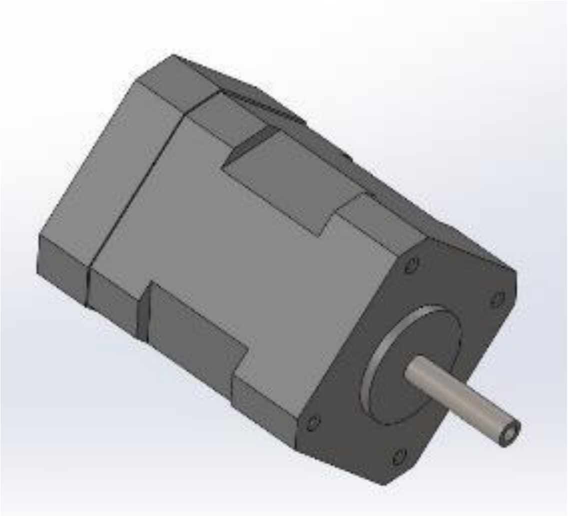
X3 Hall Effect Thruster

- High impulse of 2,470 seconds
- Requires 204 kW during spin-up
- Spin-up Time: 28 hours
- Fuel Required: 360 kg



Torque Cancelling Motor

- Motor will be connected to the rotational shaft inside the bearing assembly
- Torque from Friction: 0.078 Nm
- Motor Torque Available: 0.3 Nm



Paravalux PM8S DC

Expandable Shaft Robotic System

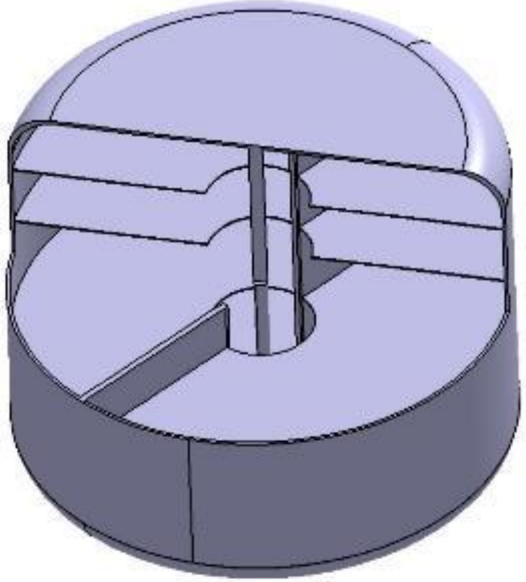
- Requirement: Expandable shaft robotic system must have fine motor skills
  - Needs to be able to make connections between supports and bracing
  - Needs to be able to wrap Velcro around supports to connect supports to shroud
  - Must be able to make repairs and perform maintenance as necessary
- Steel cable will be used as a track through the shaft

Shadow Teleoperation Development System

Storage Pod Robotic System

- Machine learning robotic arm will pull supplies from the storage pod and transfer them to the expandable shaft robot for transfer to habitat pod
- The arm will move a long a rod in the center of the pod to reach supplies
- Recommend that the robotic arm be long enough to reach to the back wall of the pod

Machine Learning Robotic Arm



Cross Sectional View of Storage Pod's Organizational System

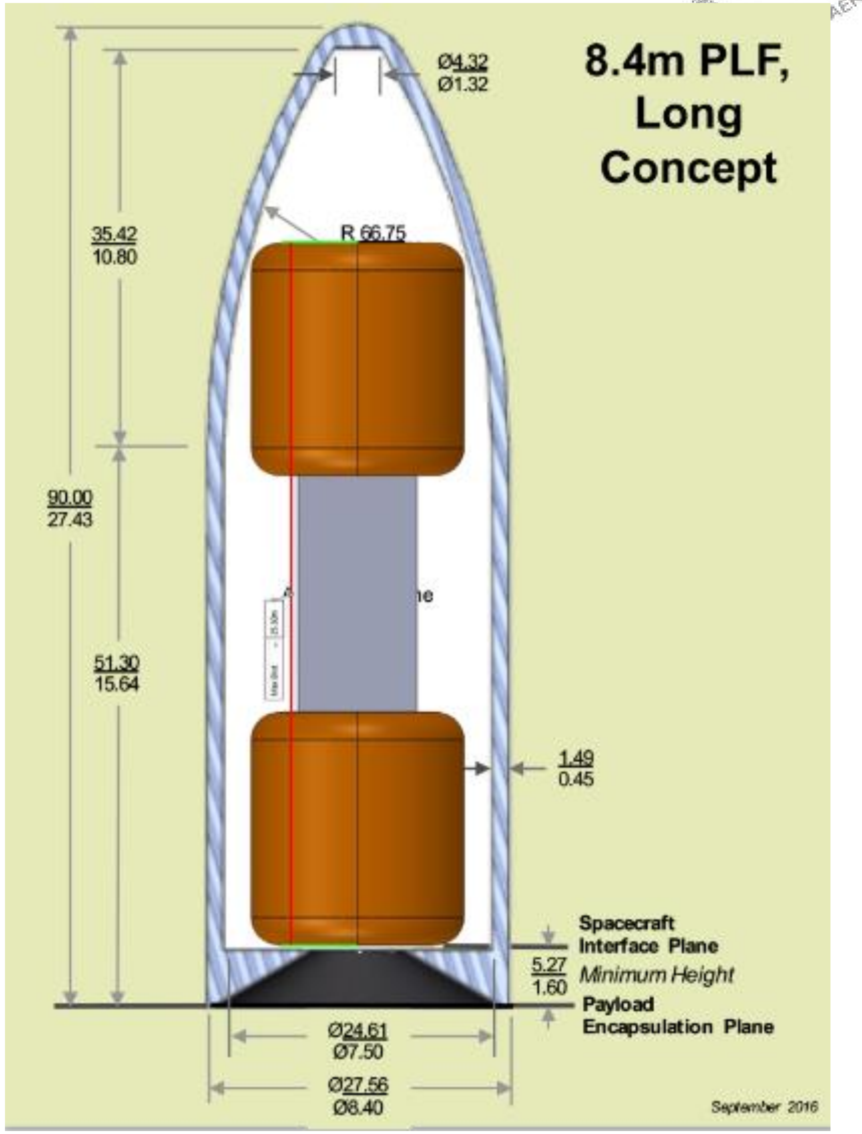
Logistics

Launches:

- Hammerhead configuration fits inside a NASA 8.4 m long SLS concept
  - Will require additional support during launch
  - Supplies will be stored inside pods for launch
- Multiple Launches Required:
  1. Pod System and Supplies
  2. Propulsion System
- NASA already had 2 launches planned
  - Baseline met

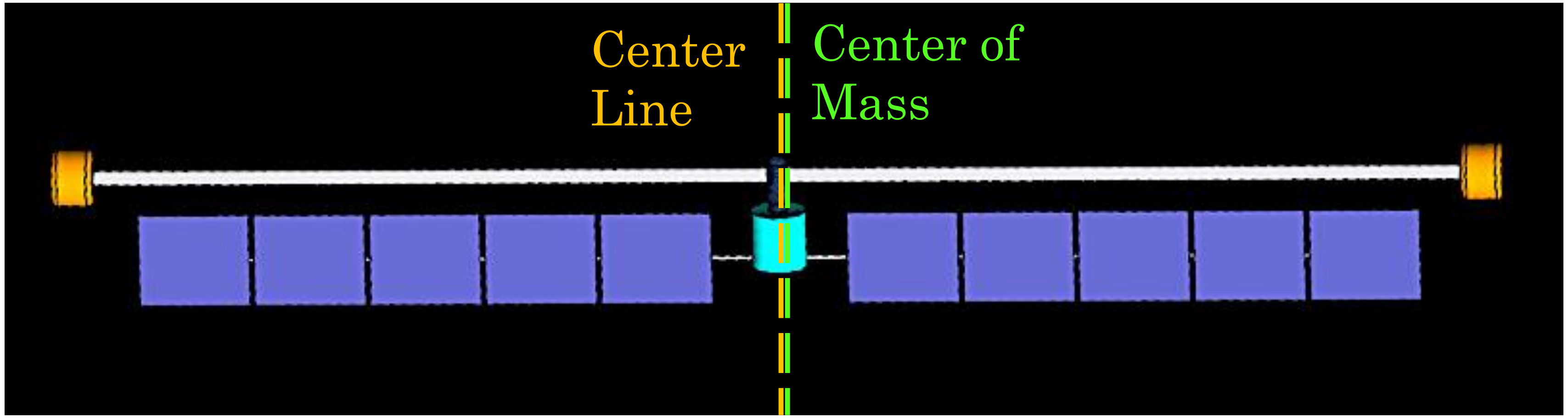
Additional Budget Required:

Engineering Development	$250 million
Expandable Shaft System	$41 million
Storage Pod Shell	$230 million
Rotational System	$1 million
Total	$522 million



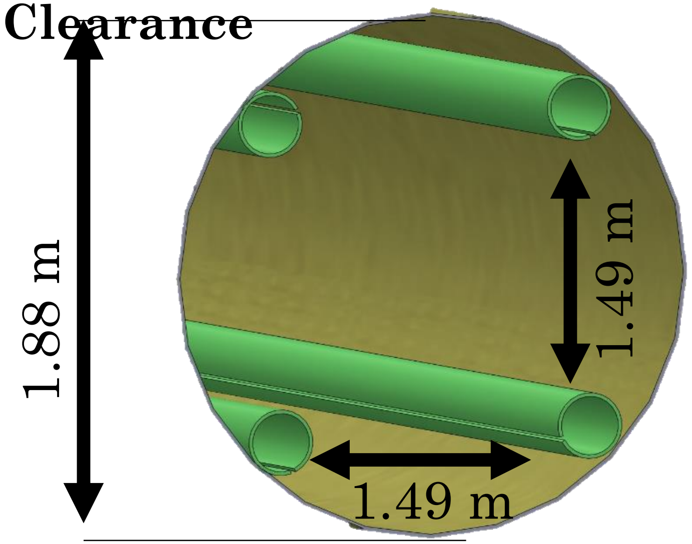
Significant Issue – Mass Balance

- The center of mass for the system is -8.14 cm from the center
- Potential problems arise when the center of mass is +/-10 cm from the center
  - Could cause the system to become unbalanced resulting in catastrophe

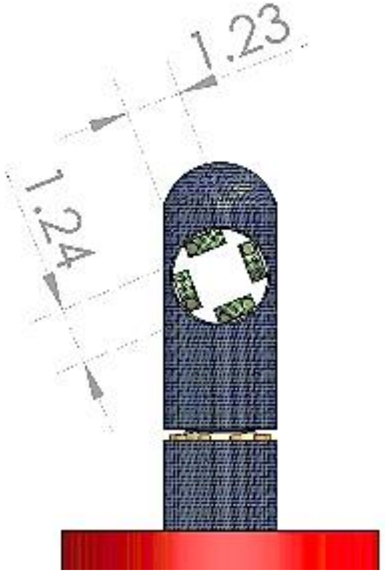


Significant Issue – Astronaut Clearance

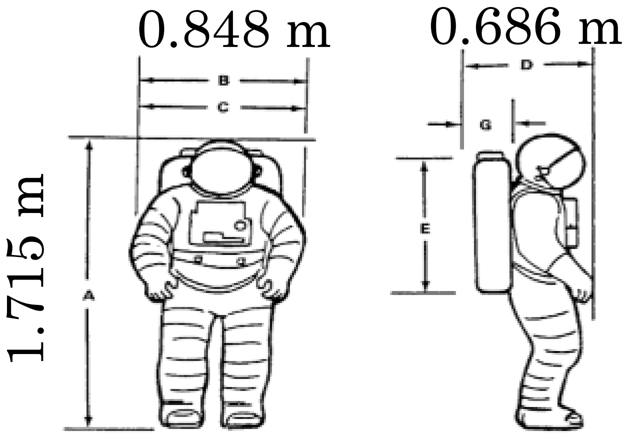
Expandable Shaft Clearance



Central Hub Clearance

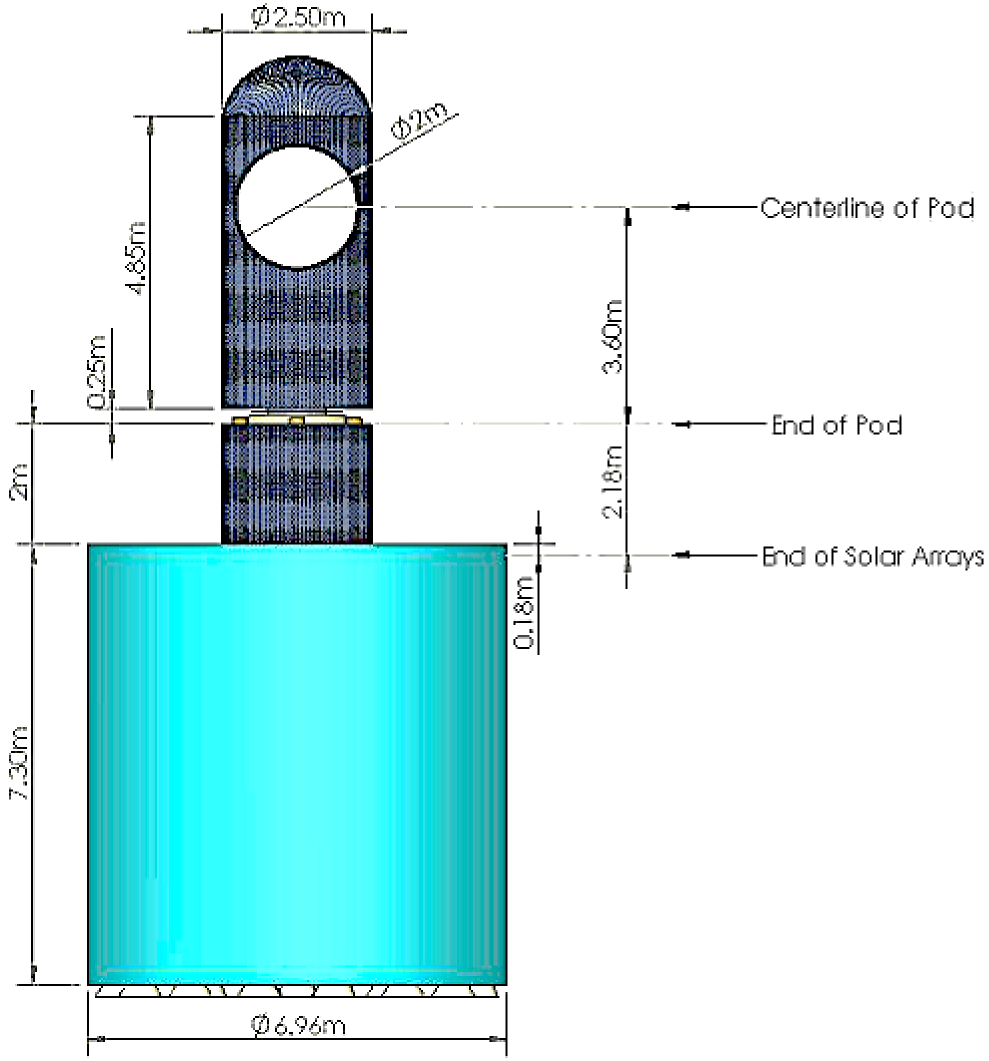


Spacesuit Dimensions



- Astronauts will need to crouch when travelling through central hub
- Astronauts will be able to move normally through expandable shaft
- Recommend spacesuit research to minimize clearance issue

Possible Issue - Solar Panel Interference



Static Solar Panel Clearance: 2.18 meters

Max Displacement of Expandable Shaft Under Load: 0.575 meters

Clearance with Expandable Shaft Under Load: 1.605 meters

- This is for static analysis only so a dynamic analysis will be necessary to see if the 1.605 meter clearance will be adequate

Schedule

- Mostly remained on schedule
- Lessons Learned:
  - CAD and FEA will always take longer to complete than estimated
  - Plan a task to take about 3x longer than first estimation
  - Models took a lot more time and money to build than anticipated
- NASA Elimination Feedback:
  - More analysis - Reasonable
  - Must calculate consumables needed – NASA supplies the consumables, was not part of the competition

Conclusions

- Launch in the hammerhead configuration and then transition into the transit configuration for electric thrust
- Using a combination of 4 BRC supports and 7 BRC brace sets will allow the shaft to withstand rotation
- Kevlar and MLI shroud will allow for thermal regulation and radiation production for the shaft
- Only requires $522 million in additional spending
- Meets most of the requirements with only of few minor issues to address
- Impacts the future of the Mars' missions if designed and implemented well

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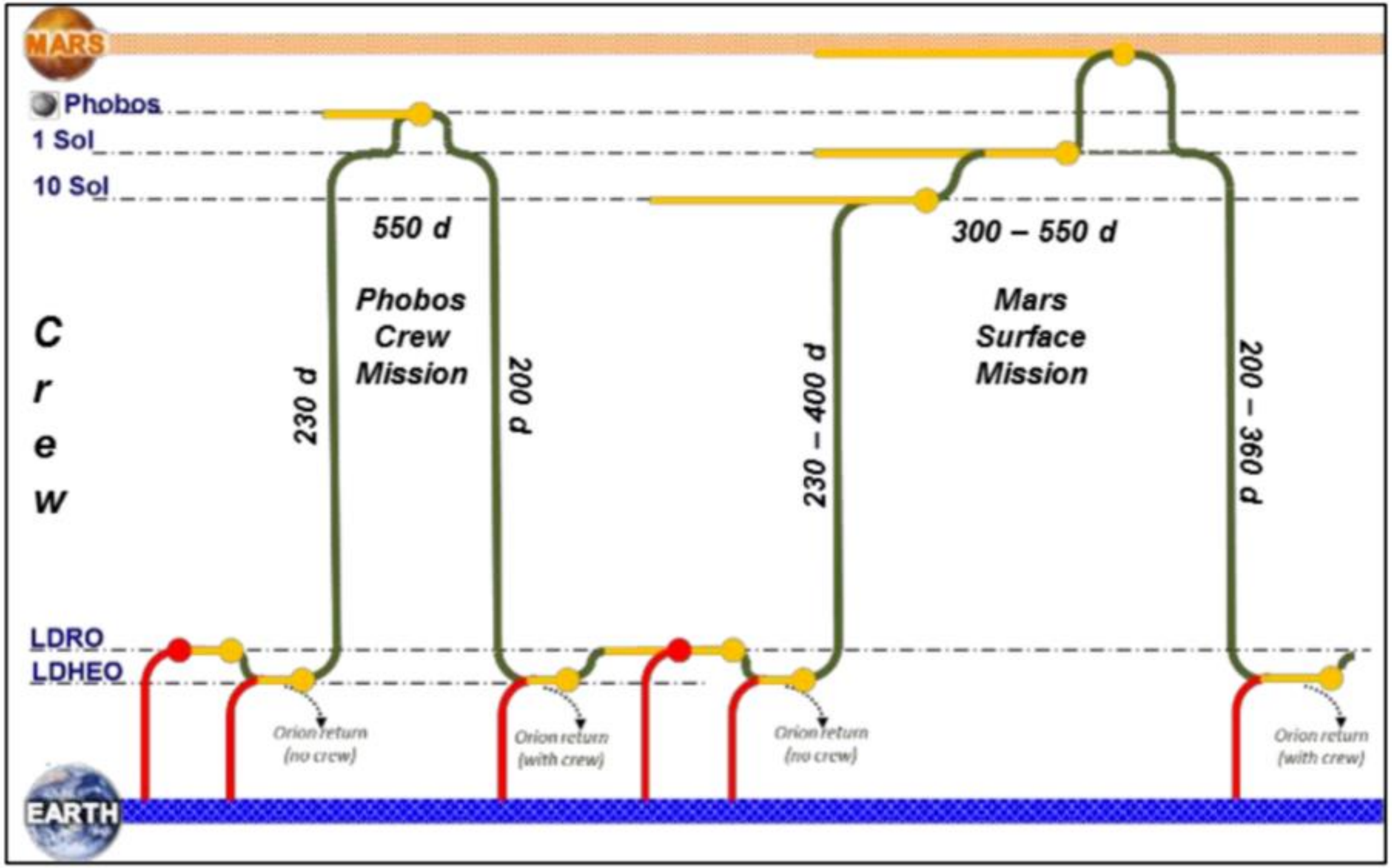
Back-Up Slides

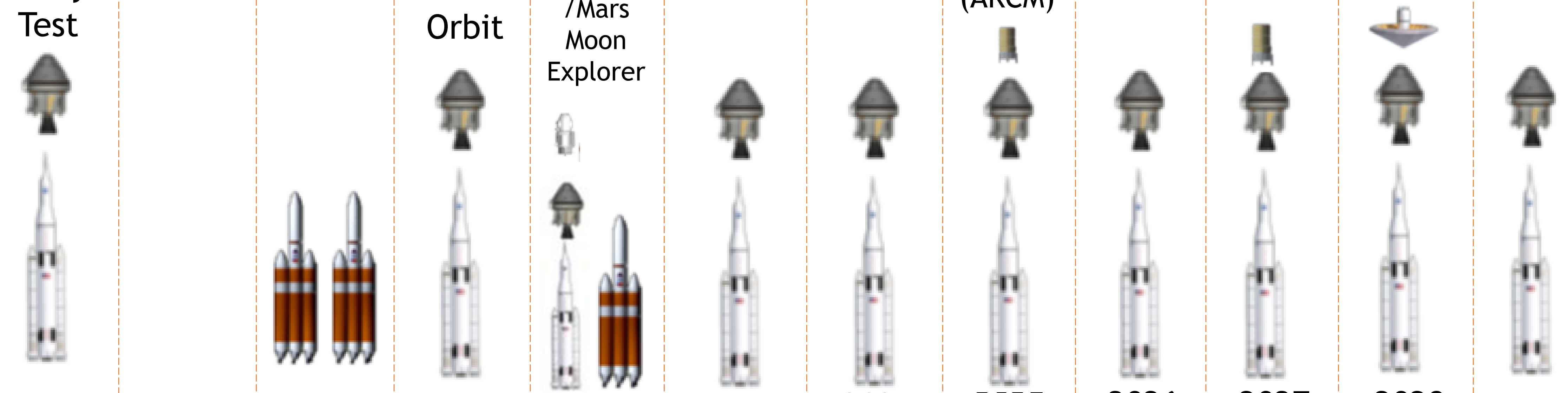
RASC-AL CONOPS



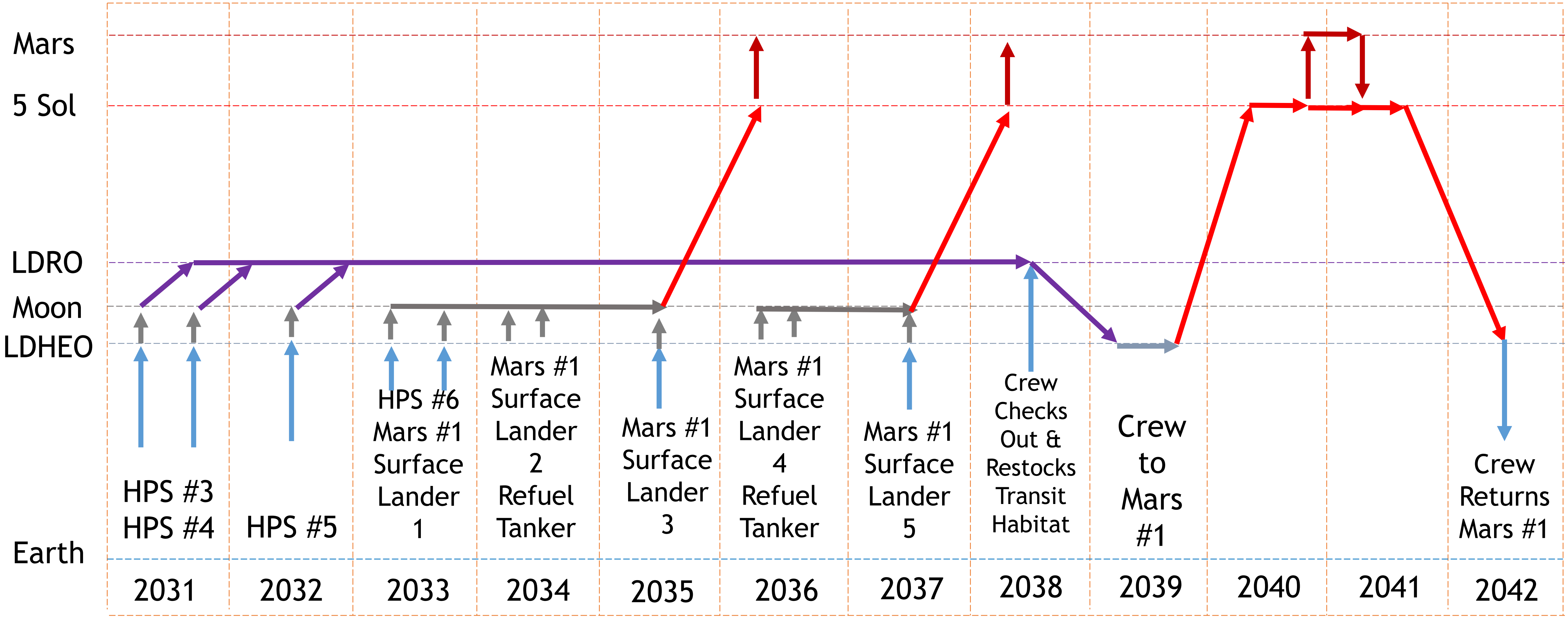
- Will need 1 additional launch from baseline

Preliminary Task Schedule

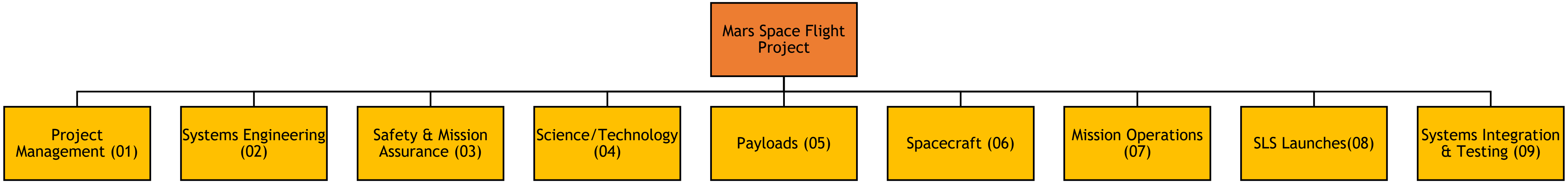
70 t EM-1 High Speed Entry Test		Mars 2020/ ARRM	105 t EM-2 Crew to Cis-Lunar Orbit	EM-3 Crew to Cis-Lunar & EAM Delivery /Mars Moon Explorer	EM-4 Crew to Cis-Lunar Orbit	EM-5 Crew to Cis-Lunar Orbit	EM-6 Crew to Cis-Lunar Orbit (ARCM)	EM-7 Crew to Cis-Lunar Orbit	EM-8 Crew to Cis-Lunar Orbit	130 t Phobos Habitat Launched to LDHEO	Crew Checkout of Phobos Habitat
2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029



Notional Launch Schedule

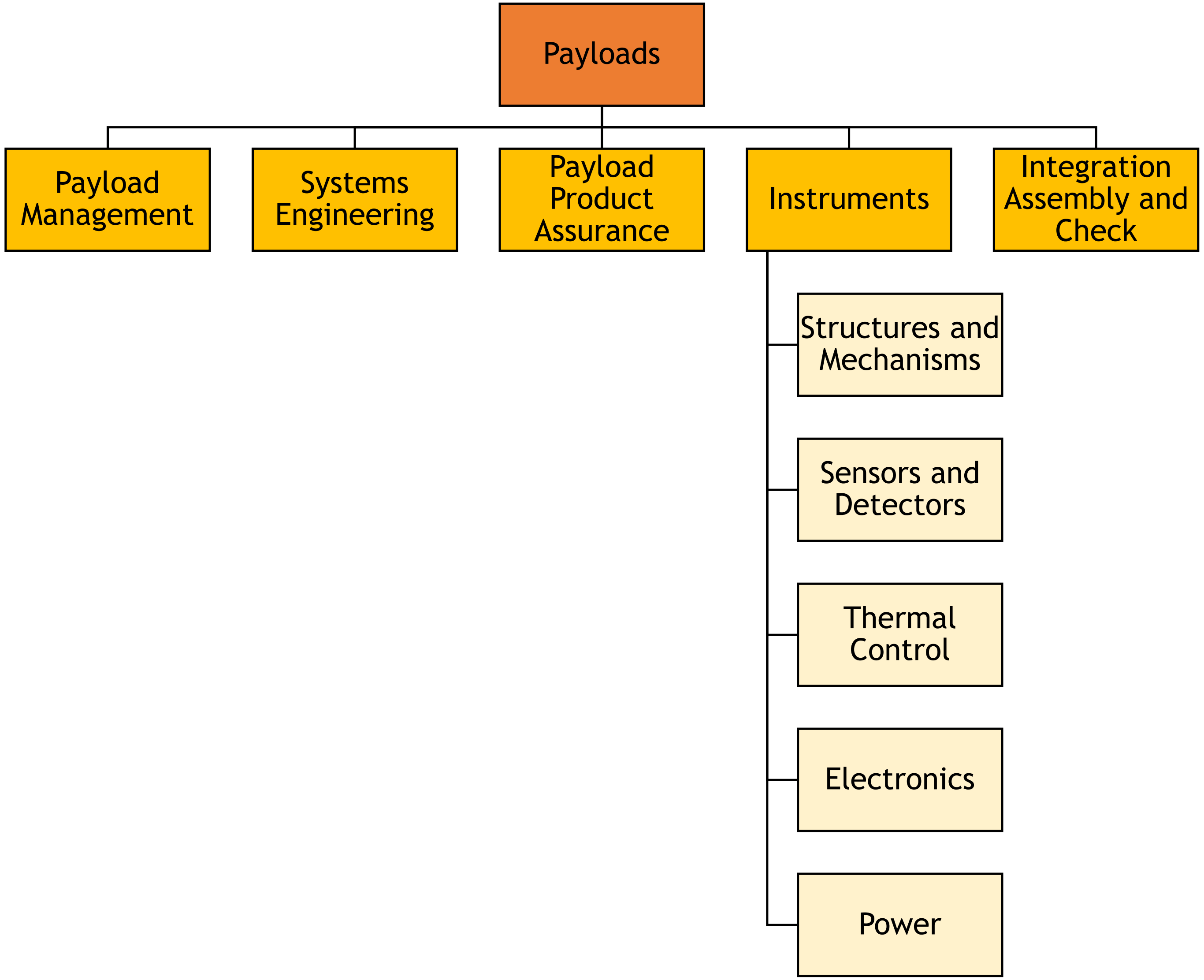


Overall Work Breakdown Structure



- Mars Space Flight Project
  - Project Management (01)
  - Systems Engineering (02)
  - Safety & Mission Assurance (03)
  - Science/Technology (04)
  - Payloads (05)
  - Spacecraft (06)
  - Mission Operations (07)
  - SLS Launches(08)
  - Systems Integration & Testing (09)

Payloads Work Breakdown Structure

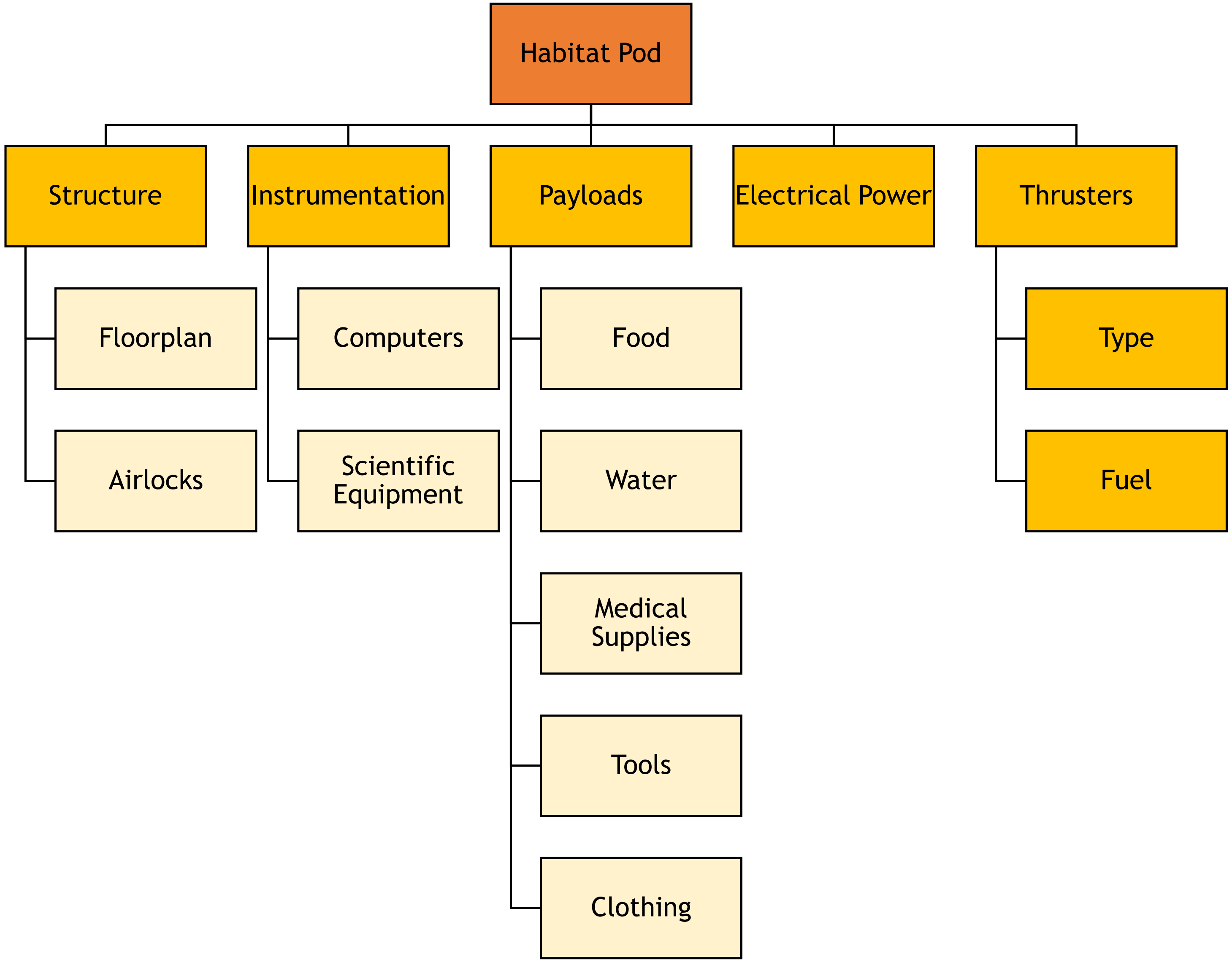


- Payloads
  - Payload Management
  - Systems Engineering
  - Payload Product Assurance
  - Instruments
    - Structures and Mechanisms
    - Sensors and Detectors
    - Thermal Control
    - Electronics
    - Power
  - Integration Assembly and Check

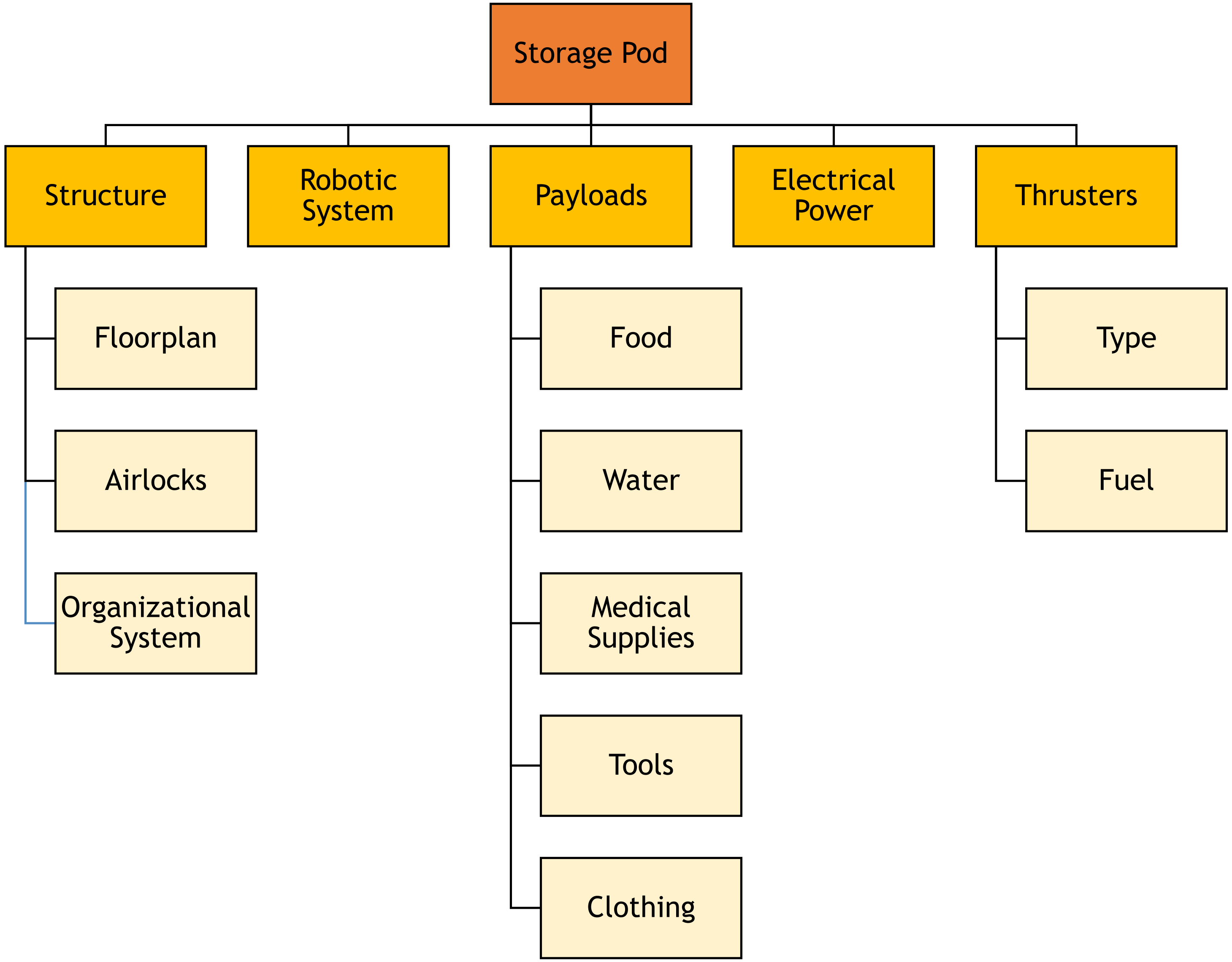
Spacecraft Work Breakdown Structure

- Spacecraft
  - Spacecraft Management
  - Systems Engineering
  - Product Assurance
  - Structures and Mechanisms
    - Habitat Pod
    - Storage Pod
    - Central Hub
    - Expandable Shaft
  - Thermal Control
  - Electrical Power
    - Solar Arrays
  - Propulsion
    - High Thrust Chemical System
    - Low Thrust Electric System
  - Communications
  - Retirement and Disposal

Habitat Pod Work Breakdown Structure



Storage Pod Work Breakdown Structure

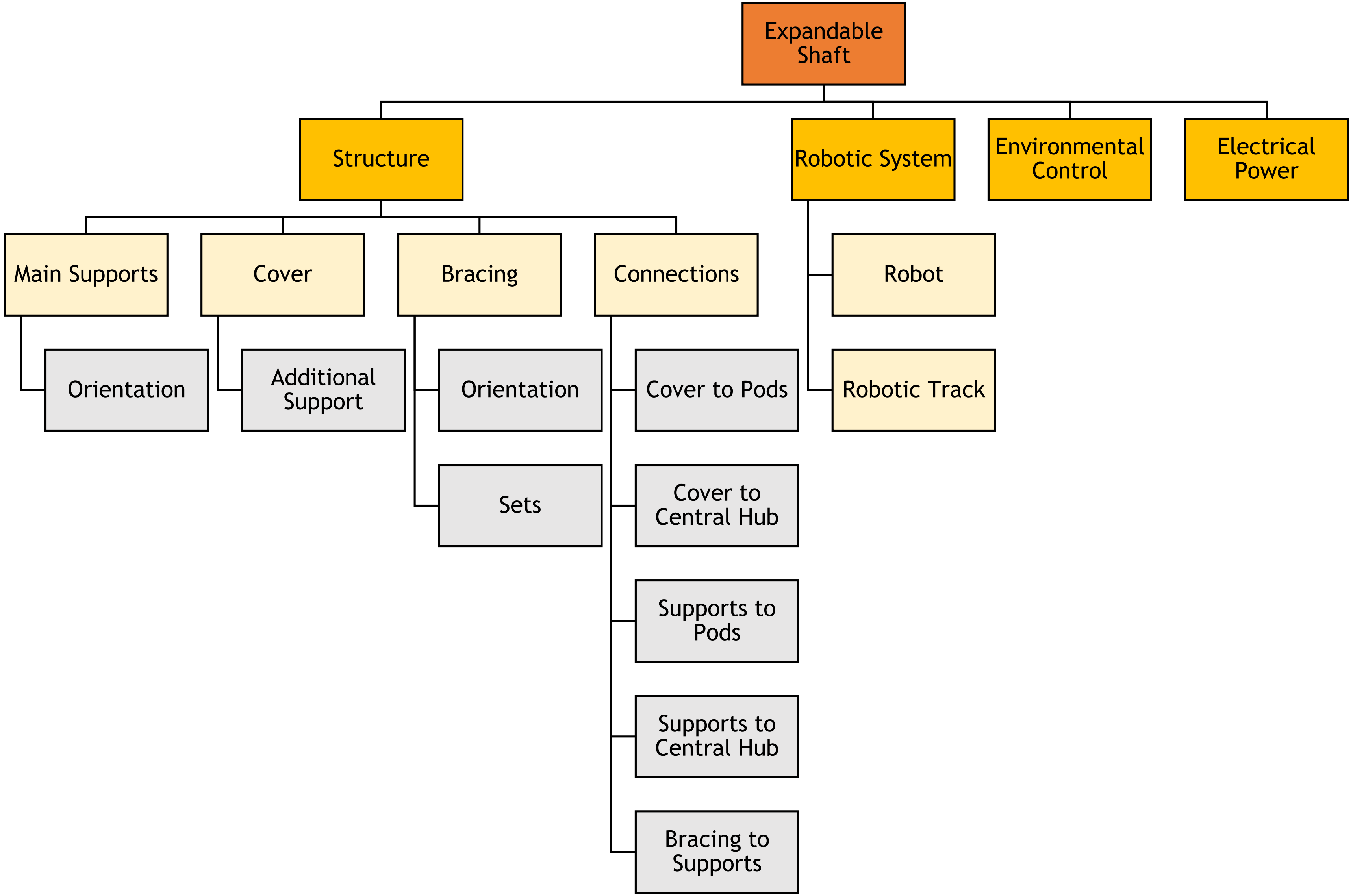


- Storage Pod
  - Structure
    - Floorplan
    - Airlocks
    - Organizational System
  - Robotic System
  - Payloads
    - Food
    - Water
    - Medical Supplies
    - Tools
    - Clothing
  - Electrical Power
  - Thrusters
    - Type
    - Fuel

Central Hub Work Breakdown Structure

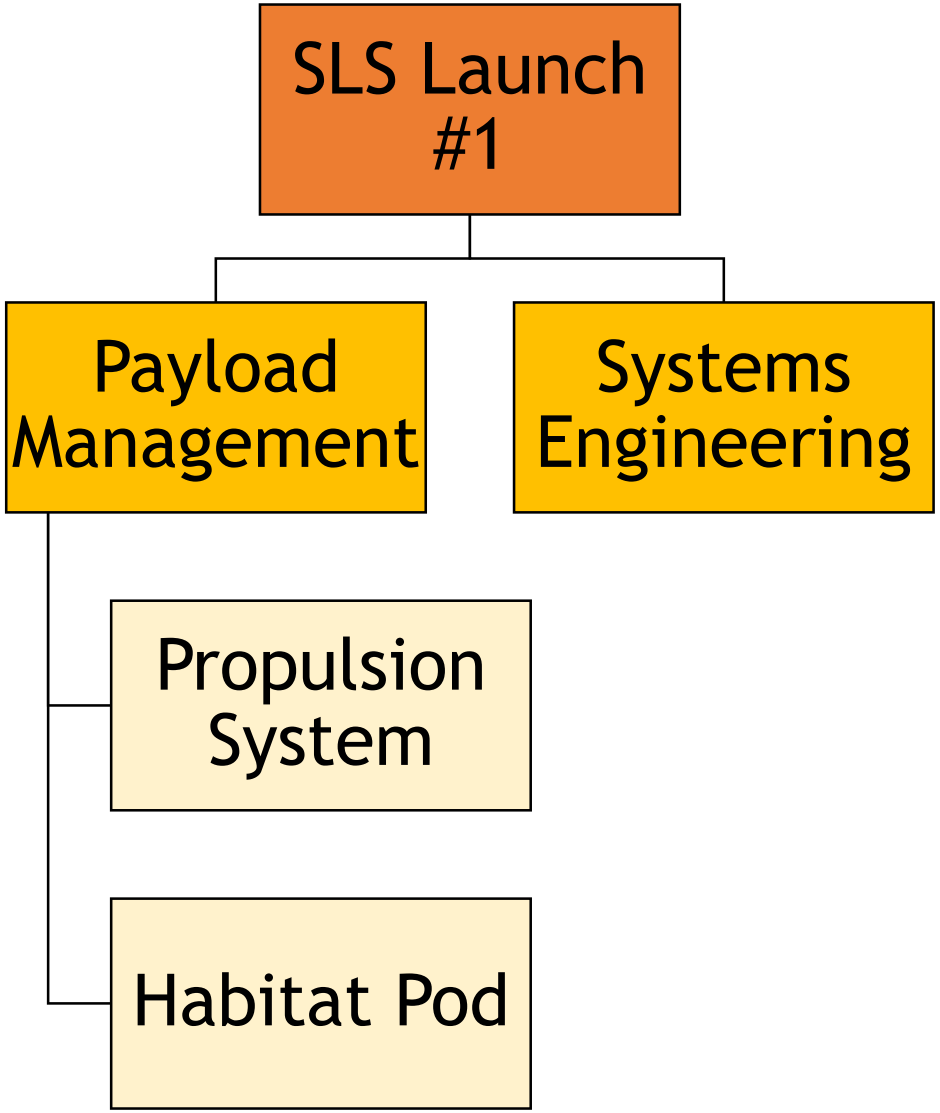
- Central Hub
  - Structure
    - Material
    - Design
  - Bearing Assembly
    - Bearing Type
    - Lubrication
  - Reels
    - Expansion and Contraction Motors
  - Cover
  - Electrical Power
  - Torque Cancelling Motor
  - Rotational Motor

Expandable Shaft Work Breakdown Structure



- Expandable Shaft
  - Structure
    - Main Supports
      - Orientation
    - Cover
      - Additional Support
    - Bracing
      - Orientation
      - Sets
    - Connections
      - Cover to Pods
      - Cover to Central Hub
      - Supports to Pods
      - Supports to Central Hub
      - Bracing to Supports
  - Robotic System
    - Robot
    - Robotic Track
  - Environmental Control
  - Electrical Power

SLS Launch #1 Work Breakdown Structure



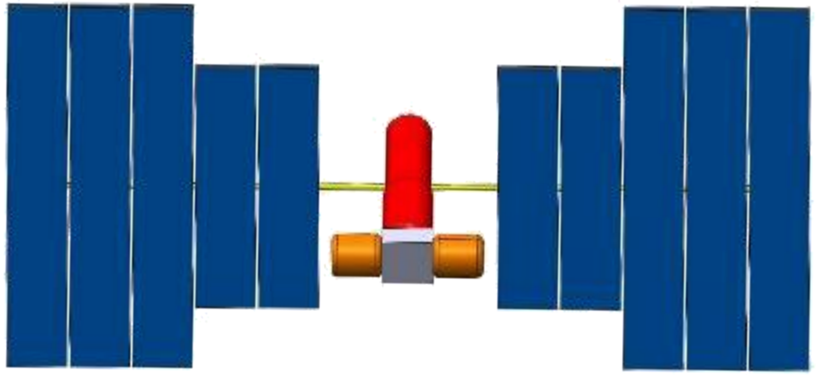
- SLS Launch #1
  - Payload Management
    - Propulsion System
    - Habitat Pod
  - Systems Engineering

SLS Launch #2 Work Breakdown Structure

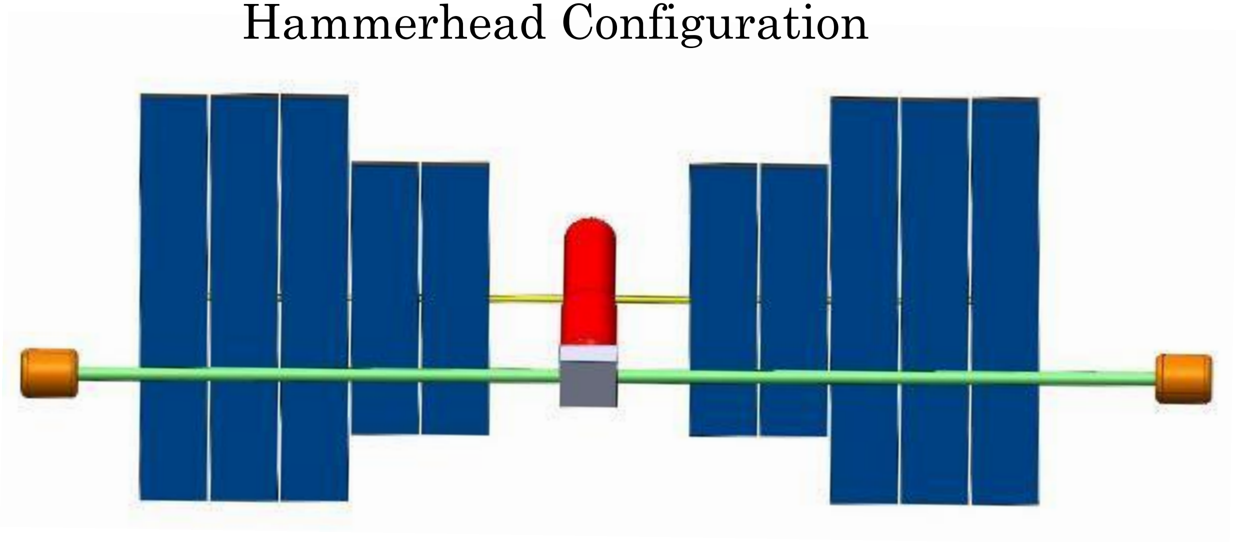
- SLS Launch #2
  - Payload Management
    - Central Hub
    - Storage Pod
    - Expandable Shaft
    - Consumables
  - Systems Engineering

Potential Design 1 – Expandable Shaft

- Benefits:
  - Easy Assembly in cis-lunar orbit
  - Lighter Materials
  - Compact Retracted Configuration
  - Quickly extends and retracts
  - Symmetrical design allows for easier Mass Balance and storage transfers
  - Ability to balance masses by varying one of the arm lengths

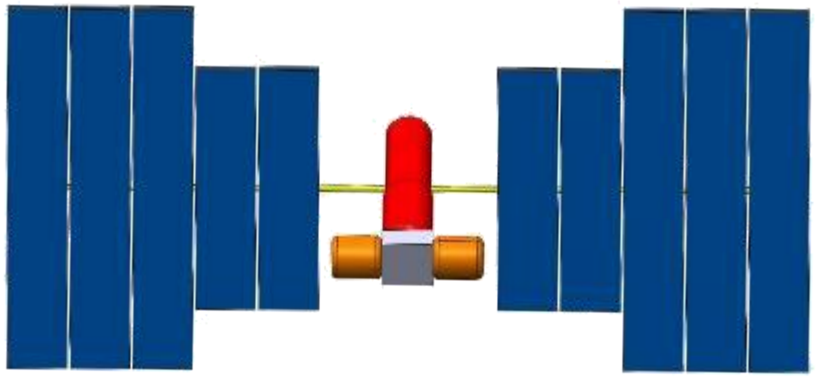


Hammerhead Configuration

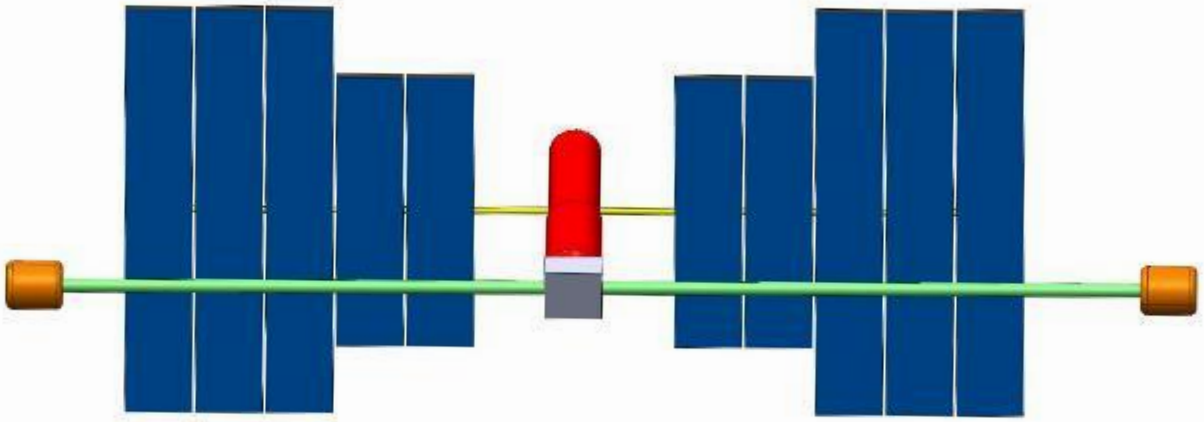


Fully Extended Configuration

Potential Design 1 – Expandable Shaft



Hammerhead Configuration

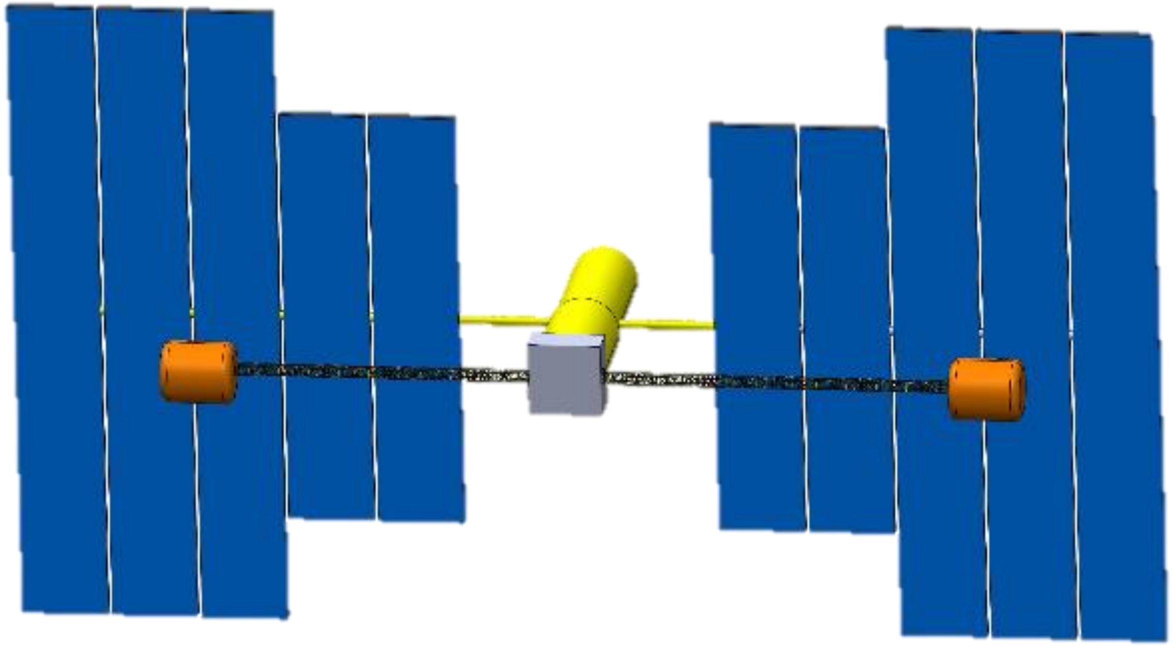


Fully Extended Configuration

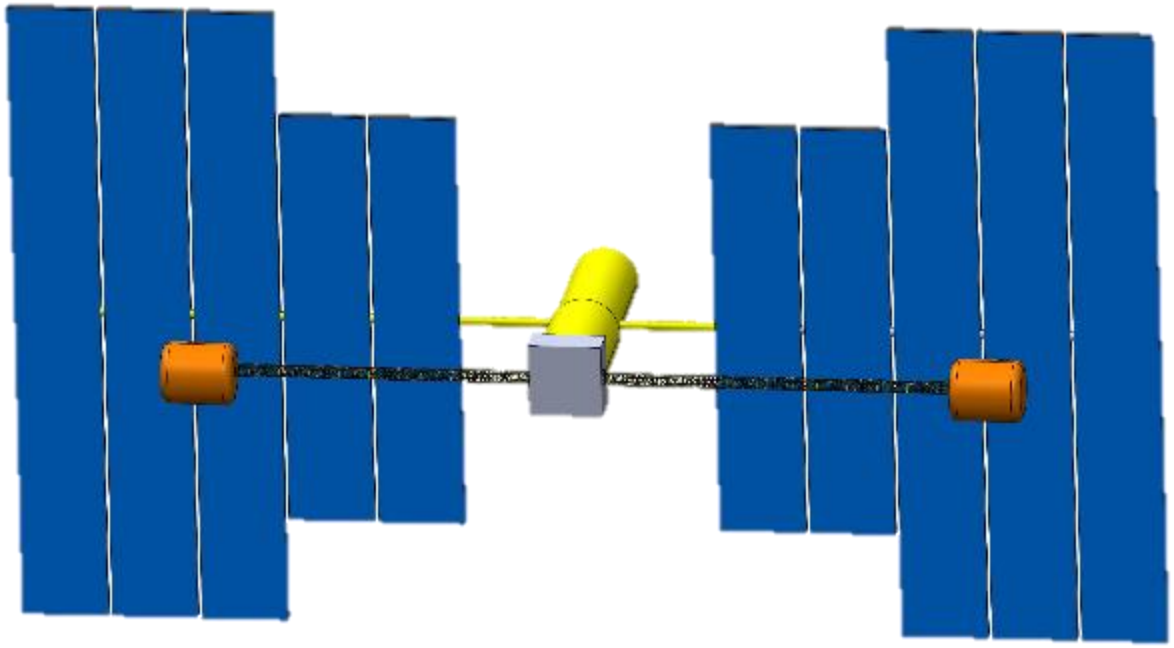
- Cons:
  - Cross Bracing will need to be added once the shaft has been extended and then removed before contracting
  - Unknown stability of the Bi-stable reeled composite during rotation
  - Large number of moving parts

Potential Design 2 – Truss

- Benefits:
  - Known stability of trusses
  - Less moving parts
  - Easier to secure piping, cables, and rails onto trusses



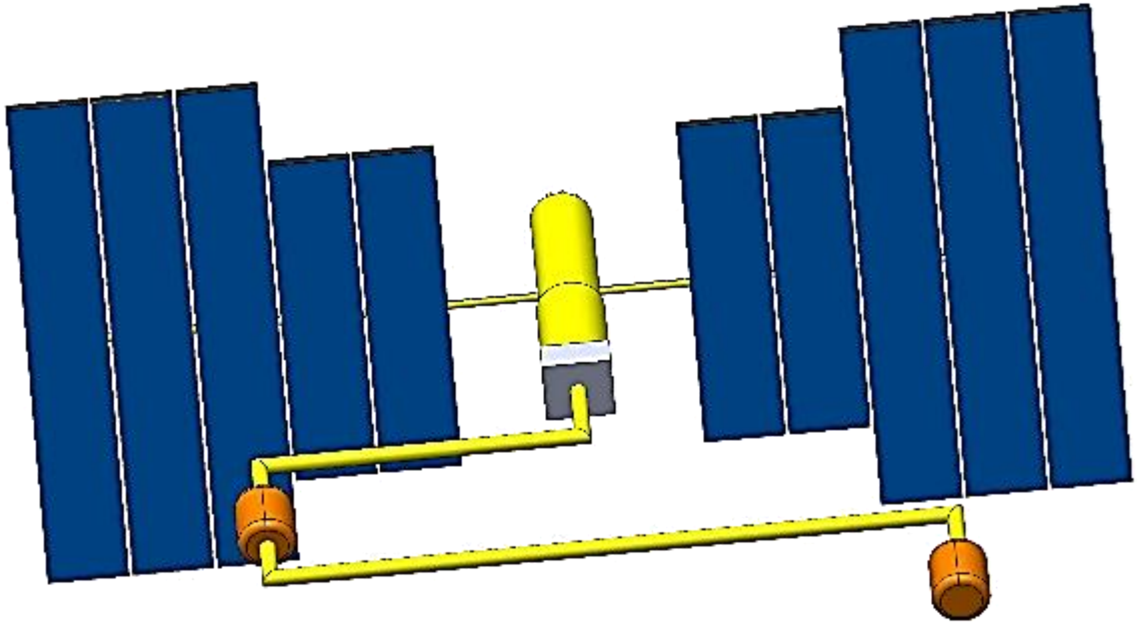
Potential Design 2 – Truss



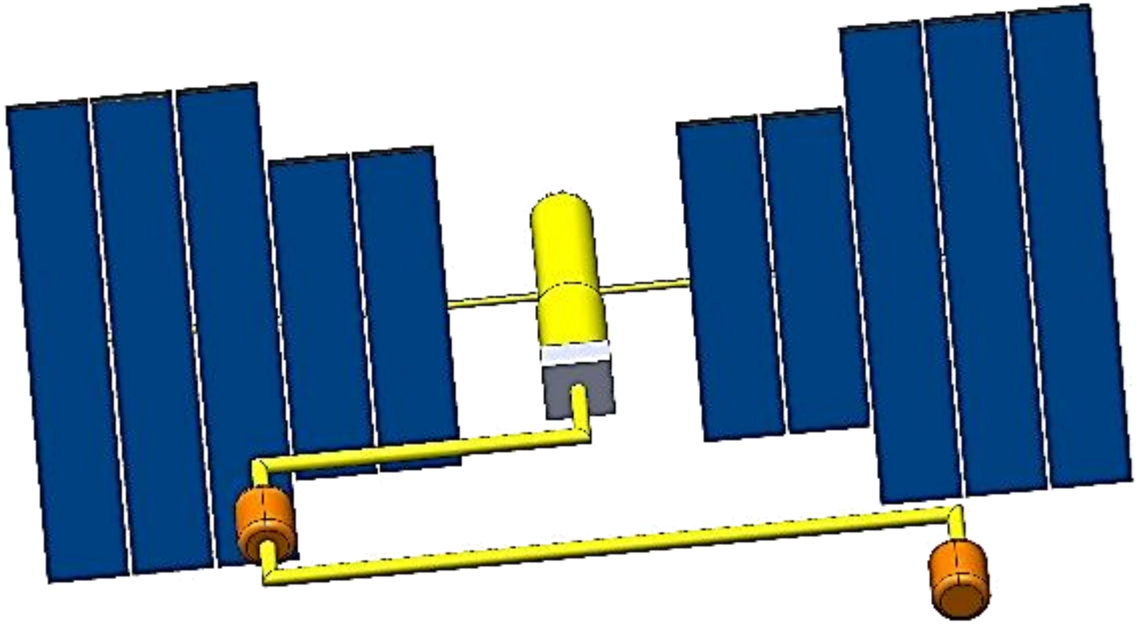
- Cons:
  - Cis-lunar orbit assembly wil be more difficult and take longer
  - Heavier Materials
  - More stress on the system during the high-thrust chemical system since it is always in the extended configuration

Potential Design 3 – Zig Zag

- Benefits:
  - Allows for a streamline configuration of the pods by stacking the pods on top of one another



Potential Design 3 – Zig Zag



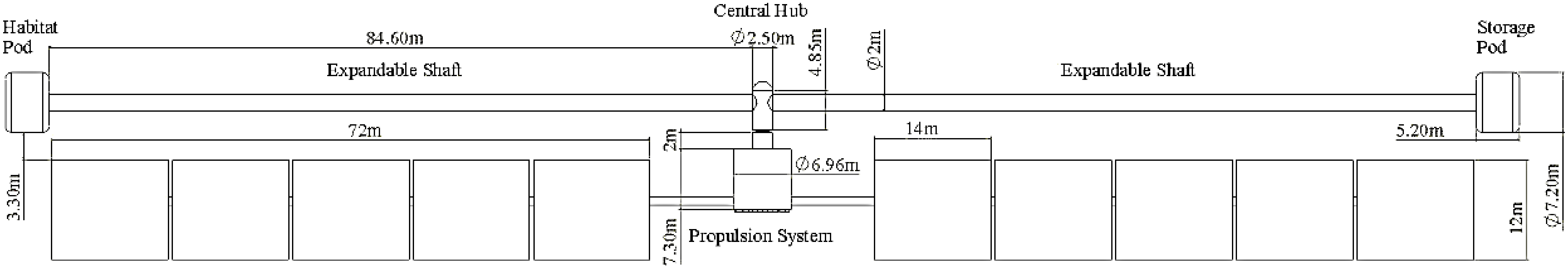
- Cons:
  - Complicated design
  - Many unknowns in how it would perform during spin-up and spin-down
  - Unsymmetrical with one pod extending further than the other
  - Difficult transfer system between pods

Selected Design – Expandable Shaft

- Preliminary Characteristics:
  - Two Pods – Habitat Pod and Storage Pod
  - Expandable Shafts made from bi-reeled composite (BRC)
  - Artificial gravity created by centrifugal force
  - Pod System Independently Rotates from propulsion system

- Performance Predictions:
  - BRC Material should perform well in tension and at the 84.6 meter lengths
  - Efficient Spin-up and spin-down using a thruster system on the pods
  - Quick expansion and contraction using motors to move the BRC supports and cover
  - Piping System will provide extra rigidity in supports
  - Magnetic bearings will help separate Rotation from the propulsion system

Final Design



Transit Configuration

System Loads

Chemical Thrust – Hammerhead Configuration, No Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	196.5 (Compression)
Moment (Nm)	982.5
Bending Stress (MPa)	0.16

Chemical Thrust – Transit Configuration, No Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	196.5 (Compression)
Moment (Nm)	1.66×10^{4}
Bending Stress (MPa)	2.71

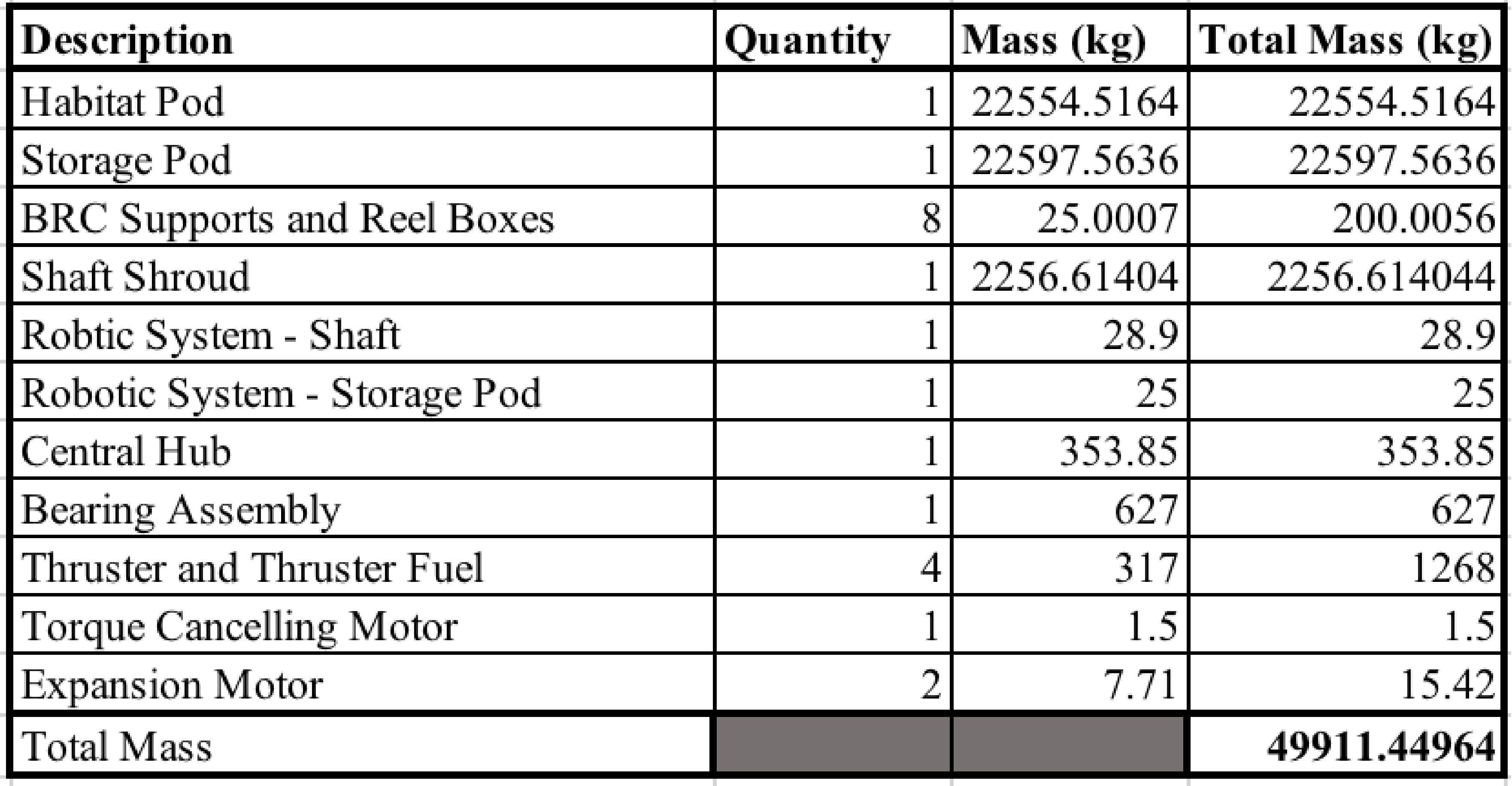
Chemical Thrust – Transit Configuration, Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	9.23×10^{4} (Tension)

Electric Thrust – Hammerhead Configuration, No Rotation	
Force of Electric Thrust (N)	8.75
Force on Pods (N)	2.27 (Compression)
Moment (Nm)	11.33
Bending Stress (MPa)	$1.85 * 10^{-3}$

Electric Thrust – Transit Configuration, No Rotation	
Force of Electric Thrust (N)	8.75
Force on Pods (N)	2.27(Compression)
Moment (Nm)	191.6
Bending Stress (MPa)	0.031

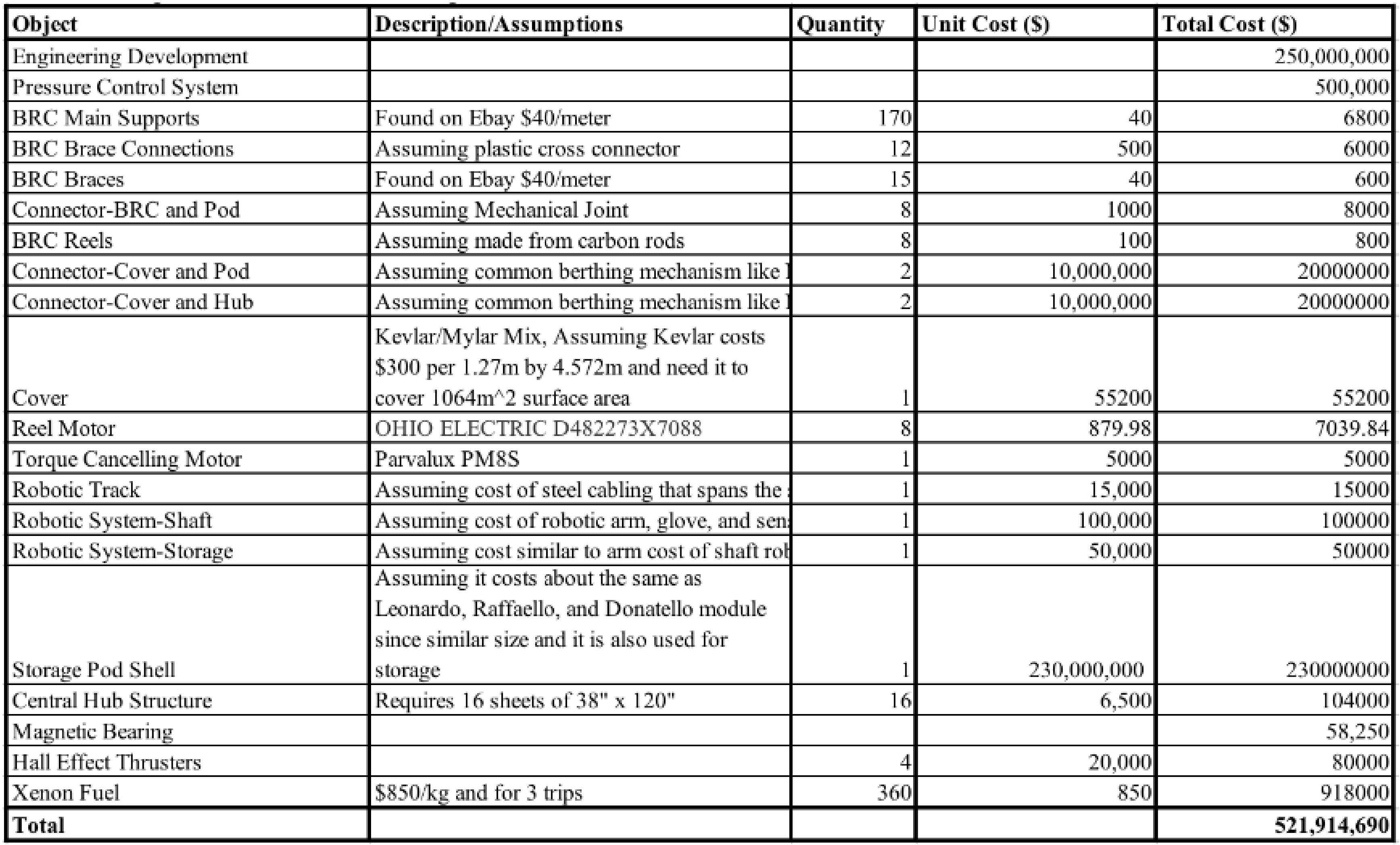
Electric Thrust – Transit Configuration, Rotation	
Force of Electric Thrust(N)	8.75
Force on Pods (N)	9.27×10^{4} (Tension)

Overall Mass Budget



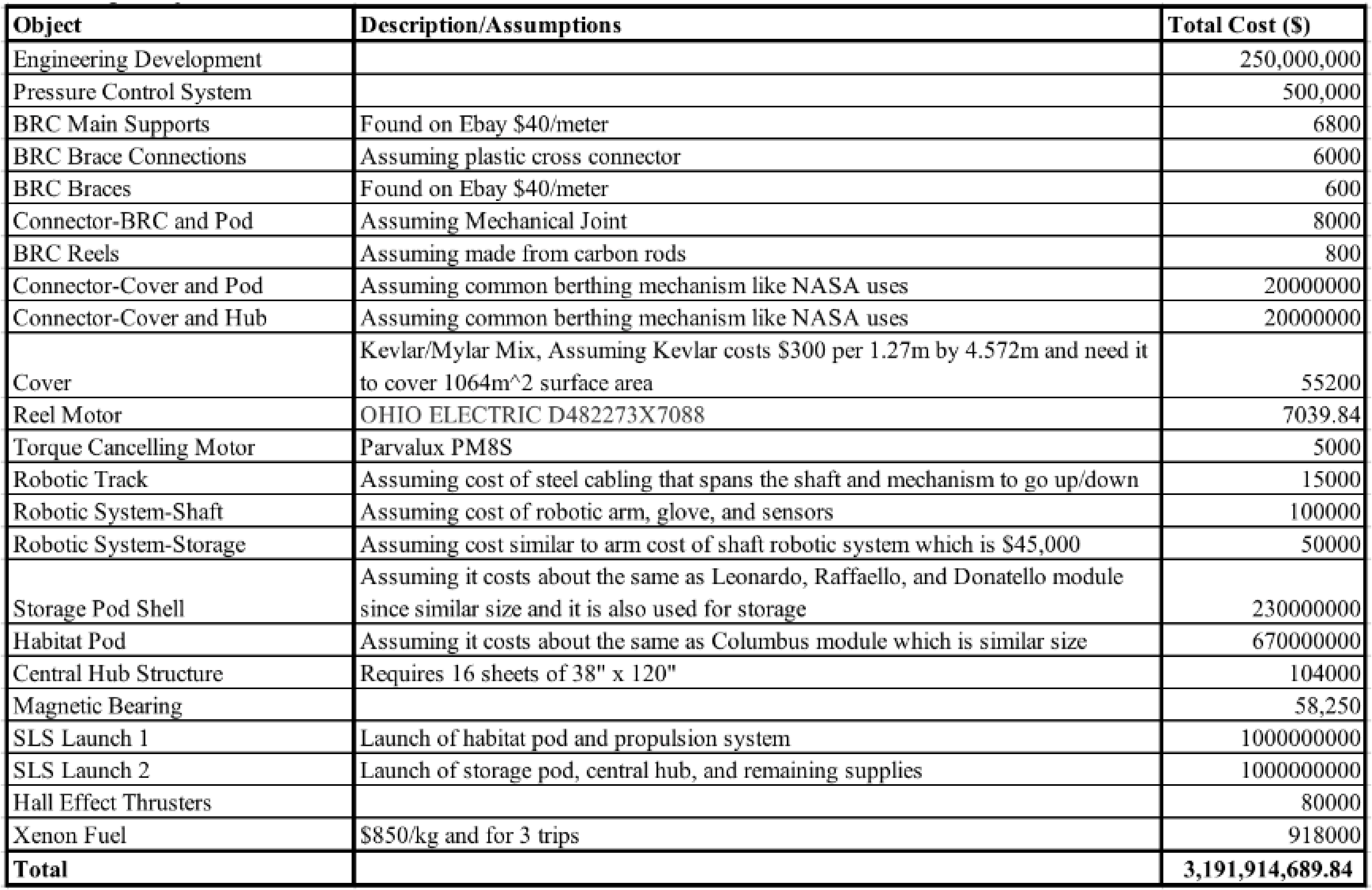
Description	Quantity	Mass (kg)	Total Mass (kg)
Habitat Pod	1	22554.5164	22554.5164
Storage Pod	1	22597.5636	22597.5636
BRC Supports and Reel Boxes	8	25.0007	200.0056
Shaft Shroud	1	2256.61404	2256.614044
Robtic System - Shaft	1	28.9	28.9
Robotic System - Storage Pod	1	25	25
Central Hub	1	353.85	353.85
Bearing Assembly	1	627	627
Thruster and Thruster Fuel	4	317	1268
Torque Cancelling Motor	1	1.5	1.5
Expansion Motor	2	7.71	15.42
Total Mass			**49911.44964**

Additional Budget Required



Object	Description/Assumptions	Quantity	Unit Cost ($)	Total Cost ($)
Engineering Development				250,000,000
Pressure Control System				500,000
BRC Main Supports	Found on Ebay $40/meter	170	40	6800
BRC Brace Connections	Assuming plastic cross connector	12	500	6000
BRC Braces	Found on Ebay $40/meter	15	40	600
Connector-BRC and Pod	Assuming Mechanical Joint	8	1000	8000
BRC Reels	Assuming made from carbon rods	8	100	800
Connector-Cover and Pod	Assuming common berthing mechanism like	2	10,000,000	20000000
Connector-Cover and Hub	Assuming common berthing mechanism like	2	10,000,000	20000000
Cover	Kevlar/Mylar Mix, Assuming Kevlar costs $300 per 1.27m by 4.572m and need it to cover 1064m^2 surface area	1	55200	55200
Reel Motor	OHIO ELECTRIC D482273X7088	8	879.98	7039.84
Torque Cancelling Motor	Parvalux PM8S	1	5000	5000
Robotic Track	Assuming cost of steel cabling that spans the	1	15,000	15000
Robotic System-Shaft	Assuming cost of robotic arm, glove, and sen	1	100,000	100000
Robotic System-Storage	Assuming cost similar to arm cost of shaft rob	1	50,000	50000
Storage Pod Shell	Assuming it costs about the same as Leonardo, Raffaello, and Donatello module since similar size and it is also used for storage	1	230,000,000	230000000
Central Hub Structure	Requires 16 sheets of 38" x 120"	16	6,500	104000
Magnetic Bearing				58,250
Hall Effect Thrusters		4	20,000	80000
Xenon Fuel	$850/kg and for 3 trips	360	850	918000
Total				**521,914,690**

Total Budget Required



Object	Description/Assumptions	Total Cost ($)
Engineering Development		250,000,000
Pressure Control System		500,000
BRC Main Supports	Found on Ebay $40/meter	6800
BRC Brace Connections	Assuming plastic cross connector	6000
BRC Braces	Found on Ebay $40/meter	600
Connector-BRC and Pod	Assuming Mechanical Joint	8000
BRC Reels	Assuming made from carbon rods	800
Connector-Cover and Pod	Assuming common berthing mechanism like NASA uses	20000000
Connector-Cover and Hub	Assuming common berthing mechanism like NASA uses	20000000
Cover	Kevlar/Mylar Mix, Assuming Kevlar costs $300 per 1.27m by 4.572m and need it to cover 1064m^2 surface area	55200
Reel Motor	OHIO ELECTRIC D482273X7088	7039.84
Torque Cancelling Motor	Parvalux PM8S	5000
Robotic Track	Assuming cost of steel cabling that spans the shaft and mechanism to go up/down	15000
Robotic System-Shaft	Assuming cost of robotic arm, glove, and sensors	100000
Robotic System-Storage	Assuming cost similar to arm cost of shaft robotic system which is $45,000	50000
Storage Pod Shell	Assuming it costs about the same as Leonardo, Raffaello, and Donatello module since similar size and it is also used for storage	230000000
Habitat Pod	Assuming it costs about the same as Columbus module which is similar size	670000000
Central Hub Structure	Requires 16 sheets of 38" x 120"	104000
Magnetic Bearing		58,250
SLS Launch 1	Launch of habitat pod and propulsion system	1000000000
SLS Launch 2	Launch of storage pod, central hub, and remaining supplies	1000000000
Hall Effect Thrusters		80000
Xenon Fuel	$850/kg and for 3 trips	918000
Total		**3,191,914,689.84**

Center of Mass

$$X = \frac{m_1 x_1 + m_2 x_2 + \ldots\ldots + m_n x_n}{m_1 + m_2 + \ldots\ldots\ldots + m_n} = \frac{\Sigma m_i x_i}{\Sigma m_i}$$

Combined Mass (Arm and Habitat Pod) = 23,783 kg

Combined Mass (Arm and Storage Pod) = 23,826 kg

Distance From Pod to Hub = 90 meters

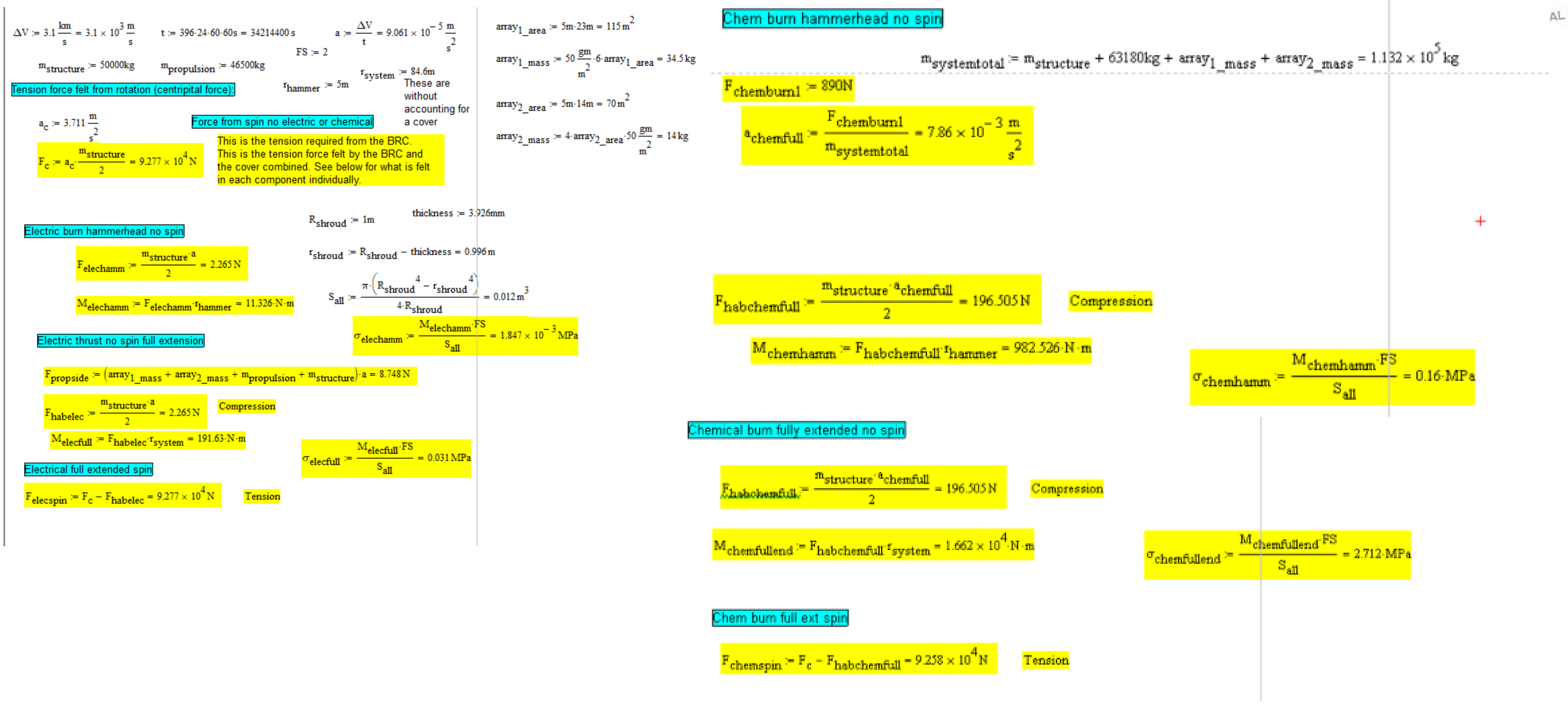
$x = \frac{23{,}783 * 90 + 23{,}826 * -90}{23{,}783 + 23{,}826}$ = -0.0814 meters from center

Radius of Expandable Shaft Calculation

$$g_{\text{Mars}} = \omega^2 * R$$

$$R = \frac{g_{\text{Mars}}}{\omega^2} = \frac{(3.711\text{m/s}^2)}{(2\text{rev/min})} = 84.6\text{m}$$

Load Calculations



$\Delta V := 3.1\,\frac{km}{s} = 3.1 \times 10^{3}\,\frac{m}{s}$

$t := 396 \cdot 24 \cdot 60 \cdot 60s = 34214400\,s$

$a := \frac{\Delta V}{t} = 9.061 \times 10^{-5}\,\frac{m}{s^{2}}$

$FS := 2$

$m_{structure} := 50000kg$

$m_{propulsion} := 46500kg$

$r_{system} := 84.6m$

These are without accounting for a cover

$r_{hammer} := 5m$

Tension force felt from rotation (centripital force):

$a_c := 3.711\,\frac{m}{s^{2}}$

$F_c := a_c \cdot \frac{m_{structure}}{2} = 9.277 \times 10^{4}\,N$

Force from spin no electric or chemical

This is the tension required from the BRC. This is the tension force felt by the BRC and the cover combined. See below for what is felt in each component individually.

$array_{1\_area} := 5m \cdot 23m = 115\,m^{2}$

$array_{1\_mass} := 50\,\frac{gm}{m^{2}} \cdot 6 \cdot array_{1\_area} = 34.5\,kg$

$array_{2\_area} := 5m \cdot 14m = 70\,m^{2}$

$array_{2\_mass} := 4 \cdot array_{2\_area} \cdot 50\,\frac{gm}{m^{2}} = 14\,kg$

Electric burn hammerhead no spin

$F_{elechamm} := \frac{m_{structure} \cdot a}{2} = 2.265\,N$

$M_{elechamm} := F_{elechamm} \cdot r_{hammer} = 11.326 \cdot N \cdot m$

$R_{shroud} := 1m$

$thickness := 3.926mm$

$r_{shroud} := R_{shroud} - thickness = 0.996\,m$

$S_{all} := \frac{\pi \cdot \left(R_{shroud}^{4} - r_{shroud}^{4}\right)}{4 \cdot R_{shroud}} = 0.012\,m^{3}$

$\sigma_{elechamm} := \frac{M_{elechamm} \cdot FS}{S_{all}} = 1.847 \times 10^{-3}\,MPa$

Electric thrust no spin full extension

$F_{propside} := \left(array_{1\_mass} + array_{2\_mass} + m_{propulsion} + m_{structure}\right) \cdot a = 8.748\,N$

$F_{habelec} := \frac{m_{structure} \cdot a}{2} = 2.265\,N$ Compression

$M_{elecfull} := F_{habelec} \cdot r_{system} = 191.63 \cdot N \cdot m$

$\sigma_{elecfull} := \frac{M_{elecfull} \cdot FS}{S_{all}} = 0.031\,MPa$

Electrical full extended spin

$F_{elecspin} := F_c - F_{habelec} = 9.277 \times 10^{4}\,N$ Tension

Chem burn hammerhead no spin

$m_{systemtotal} := m_{structure} + 63180kg + array_{1\_mass} + array_{2\_mass} = 1.132 \times 10^{5}\,kg$

$F_{chemburn1} := 890N$

$a_{chemfull} := \frac{F_{chemburn1}}{m_{systemtotal}} = 7.86 \times 10^{-3}\,\frac{m}{s^{2}}$

$F_{habchemfull} := \frac{m_{structure} \cdot a_{chemfull}}{2} = 196.505\,N$ Compression

$M_{chemhamm} := F_{habchemfull} \cdot r_{hammer} = 982.526 \cdot N \cdot m$

$\sigma_{chemhamm} := \frac{M_{chemhamm} \cdot FS}{S_{all}} = 0.16 \cdot MPa$

Chemical burn fully extended no spin

$F_{habchemfull} := \frac{m_{structure} \cdot a_{chemfull}}{2} = 196.505\,N$ Compression

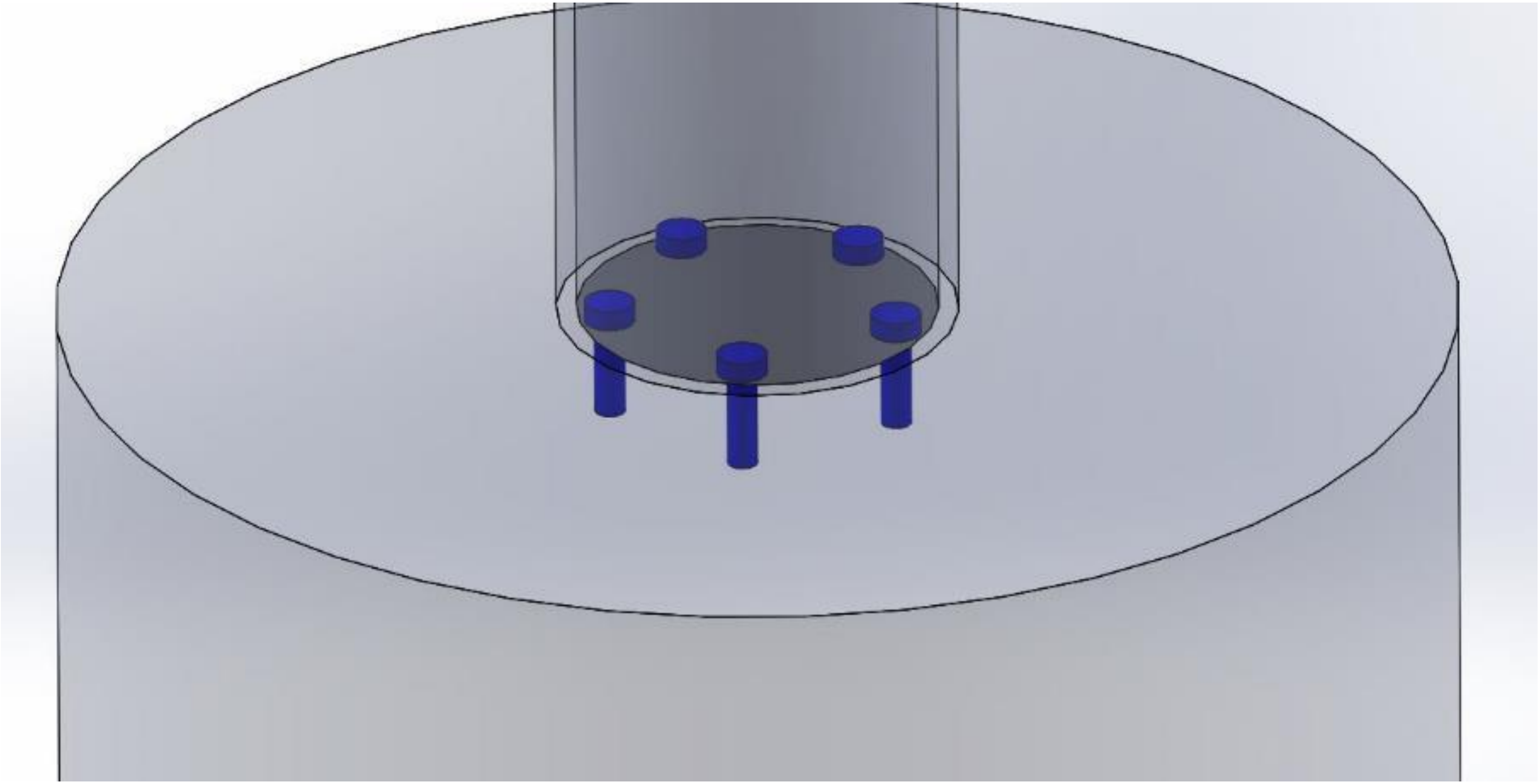
$M_{chemfullend} := F_{habchemfull} \cdot r_{system} = 1.662 \times 10^{4}\,N \cdot m$

$\sigma_{chemfullend} := \frac{M_{chemfullend} \cdot FS}{S_{all}} = 2.712 \cdot MPa$

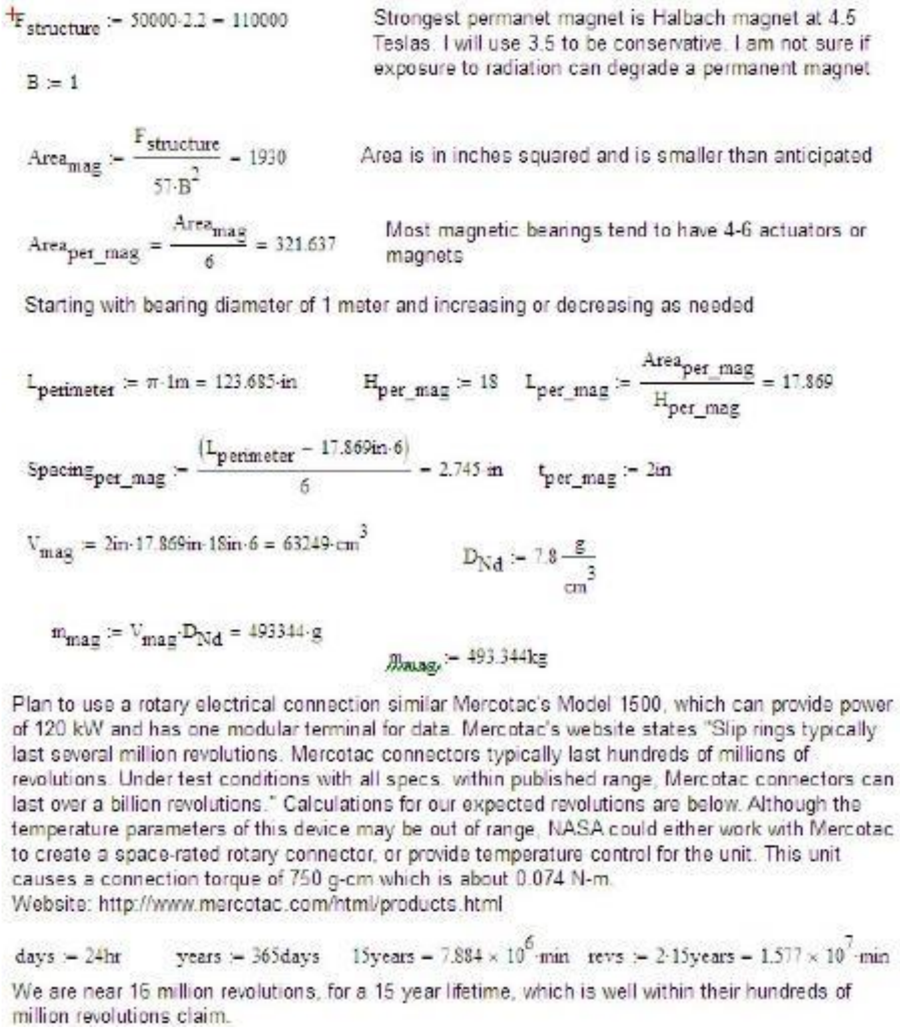
Chem burn full ext spin

$F_{chemspin} := F_c - F_{habchemfull} = 9.258 \times 10^{4}\,N$ Tension

Central Hub and Propulsion Connection



Bearing Calculations



$F_{structure} := 50000 \cdot 2.2 = 110000$

Strongest permanet magnet is Halbach magnet at 4.5 Teslas. I will use 3.5 to be conservative. I am not sure if exposure to radiation can degrade a permanent magnet

$B := 1$

$Area_{mag} := \frac{F_{structure}}{57 \cdot B^2} = 1930$

Area is in inches squared and is smaller than anticipated

$Area_{per\_mag} = \frac{Area_{mag}}{6} = 321.637$

Most magnetic bearings tend to have 4-6 actuators or magnets

Starting with bearing diameter of 1 meter and increasing or decreasing as needed

$L_{perimeter} := \pi \cdot 1\text{m} = 123.685 \cdot \text{in}$ $\quad H_{per\_mag} := 18$ $\quad L_{per\_mag} := \frac{Area_{per\_mag}}{H_{per\_mag}} = 17.869$

$Spacing_{per\_mag} := \frac{(L_{perimeter} - 17.869\text{in} \cdot 6)}{6} = 2.745\text{ in}$ $\quad t_{per\_mag} := 2\text{in}$

$V_{mag} := 2\text{in} \cdot 17.869\text{in} \cdot 18\text{in} \cdot 6 = 63249 \cdot \text{cm}^3$ $\quad D_{Nd} := 7.8 \frac{\text{g}}{\text{cm}^3}$

$m_{mag} := V_{mag} \cdot D_{Nd} = 493344 \cdot \text{g}$

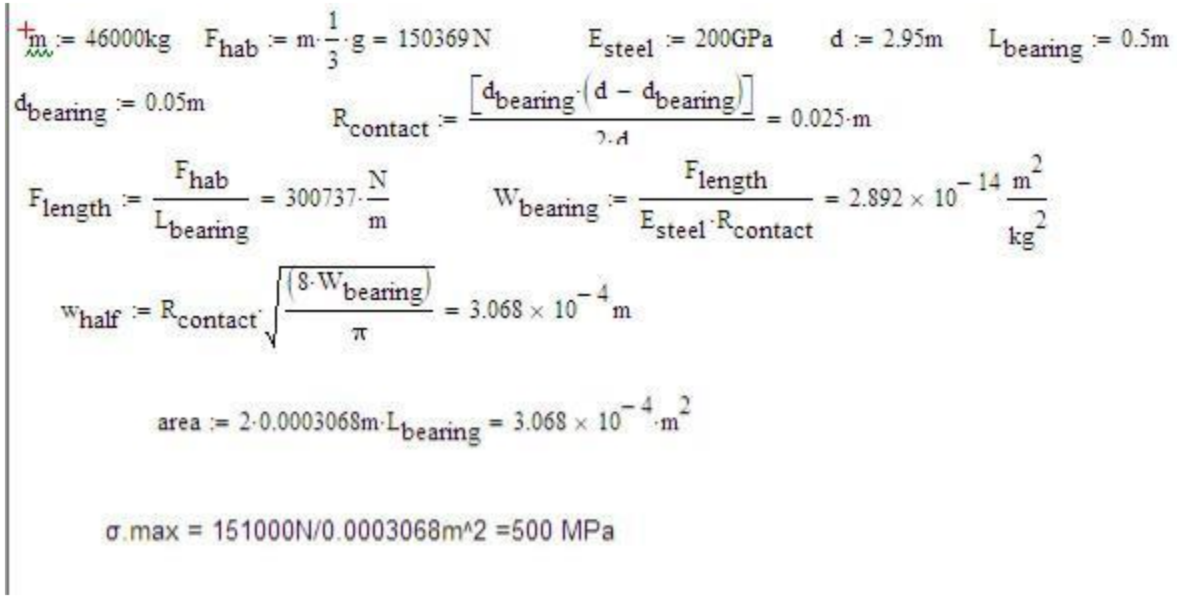
$m_{mag} := 493.344\text{kg}$

Plan to use a rotary electrical connection similar Mercotac's Model 1500, which can provide power of 120 kW and has one modular terminal for data. Mercotac's website states "Slip rings typically last several million revolutions. Mercotac connectors typically last hundreds of millions of revolutions. Under test conditions with all specs. within published range, Mercotac connectors can last over a billion revolutions." Calculations for our expected revolutions are below. Although the temperature parameters of this device may be out of range, NASA could either work with Mercotac to create a space-rated rotary connector, or provide temperature control for the unit. This unit causes a connection torque of 750 g-cm which is about 0.074 N-m.
Website: http://www.mercotac.com/html/products.html

$days := 24\text{hr}$ $\quad years := 365\text{days}$ $\quad 15\text{years} = 7.884 \times 10^{6} \cdot \text{min}$ $\quad revs := 2 \cdot 15\text{years} = 1.577 \times 10^{7} \cdot \text{min}$

We are near 16 million revolutions, for a 15 year lifetime, which is well within their hundreds of million revolutions claim.

Magnetic Bearings



$m := 46000\text{kg}$ $\quad F_{hab} := m \cdot \frac{1}{3} \cdot g = 150369\text{ N}$ $\quad E_{steel} := 200\text{GPa}$ $\quad d := 2.95\text{m}$ $\quad L_{bearing} := 0.5\text{m}$

$d_{bearing} := 0.05\text{m}$ $\quad R_{contact} := \frac{[d_{bearing} \cdot (d - d_{bearing})]}{2 \cdot d} = 0.025 \cdot \text{m}$

$F_{length} := \frac{F_{hab}}{L_{bearing}} = 300737 \cdot \frac{\text{N}}{\text{m}}$ $\quad W_{bearing} := \frac{F_{length}}{E_{steel} \cdot R_{contact}} = 2.892 \times 10^{-14} \frac{\text{m}^2}{\text{kg}^2}$

$w_{half} := R_{contact} \cdot \sqrt{\frac{(8 \cdot W_{bearing})}{\pi}} = 3.068 \times 10^{-4}\text{m}$

$area := 2 \cdot 0.0003068\text{m} \cdot L_{bearing} = 3.068 \times 10^{-4} \cdot \text{m}^2$

σ.max = 151000N/0.0003068m^2 =500 MPa

Roller Bearings

Fixed vs Expandable Trade Study

	Fixed	**Expandable**
Achieve 84.6 meter length	Yes	Yes
Stable at 84.6 meters	Yes	Yes
Stable During Rotation	Yes	Yes with bracing
Material	Metal	Composite
Mass	Heavier	Lighter
Cost	Expensive	Moderate-Expensive
Technology	Mature	Newer
Launch	Must launch with structure in place	Can launch with structure contracted
Launch Stresses on System	Higher because it is launched fully extended	Lower because it is launched fully contracted

- Chosen Design: Expandable

Expandable Trade Study

	BRC	Telescopic	Self Building Truss	Inflatable	Cable
Achieve 84.6 Meter Length	Yes	Yes	Yes	Yes	Yes
Stable at 84.6 Meters	Yes	Yes	Yes	Unknown	Yes if anchored correctly
Stable Under Rotation	Yes with bracing	Yes	Yes	Unknown	No
Material	Carbon Fiber	Composite	Metal	Kevlar	Metal
Mass	Light	Moderate	Heavy	Light	Moderate
Cost	Moderate-Expansive	Moderate-Expensive	Expensive	Expensive	Moderate
Technological Readiness	Newer	Newer	New	New	Mature

- Chosen Design: Bi-Stable Reeled Composite (BRC)

BRC Trade Study

	RolaTube	**Astrotube**	**ROCCOR**
84.6 Meter Length	Yes	No	No
Stable at 84.6 Meters	Yes	No	No
Mass	436 g/m^2	Unknown	0.66 kg/m
Deployment	Reel Motor	Reel Motor	Reel Motor
Cost	Lower than traditional space booms	Lower than traditional space booms	Unknown
Rigidization	Uses BRC properties	Embedded Conductors	Embedded Conductors
Material	Carbon PEEK	Carbon Fiber	Carbon Fiber
Technological Readiness	Yes	Needs Development	Needs Development

- Chosen Design: RolaTube

BRC Expansion Motor Trade Study

	Gear Box and Electric Motor	**Hydraulic Actuation**	**Pneumatic Actuation**
Speed	Slow	Fast	Fast
Mass	Moderate	Low-Moderate	Low-Moderate
Power Usage	Moderate-High	Low-Moderate	Low-Moderate
Size	Bigger	Smaller but requires large hydraulic fluid tanks nearby	Smaller but requires large compressed air tanks nearby
Maintenance	Minimal	Potential congestion in fluid lines or leaking hydraulic fluid	Accumulation of condensation could cause the system to freeze up
Complexity	Complex gear box	Simpler design	Simpler design
Expansion Time (hr.)	1	Unknown	Unknown

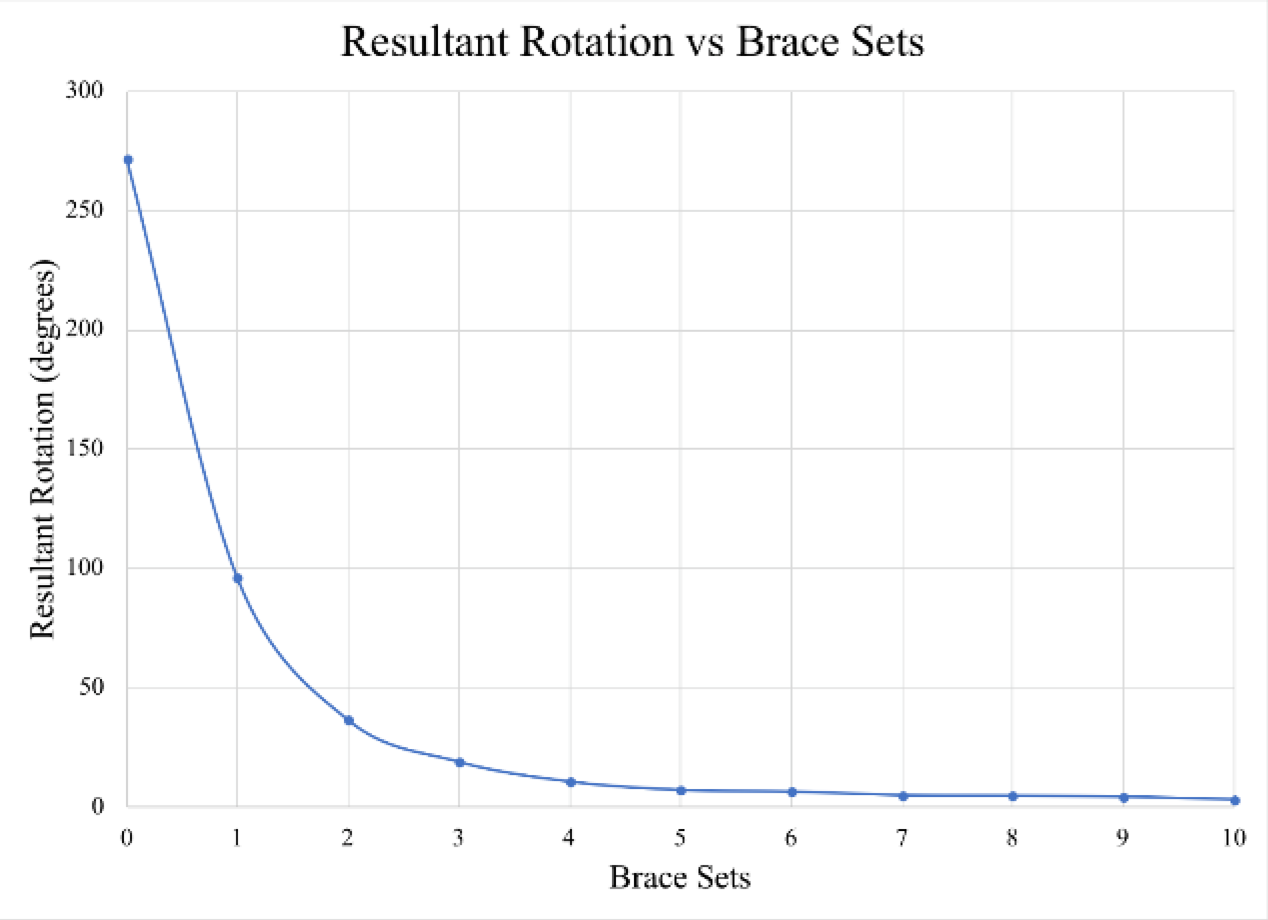
- Chosen Design: Gear Box and Electric Motor

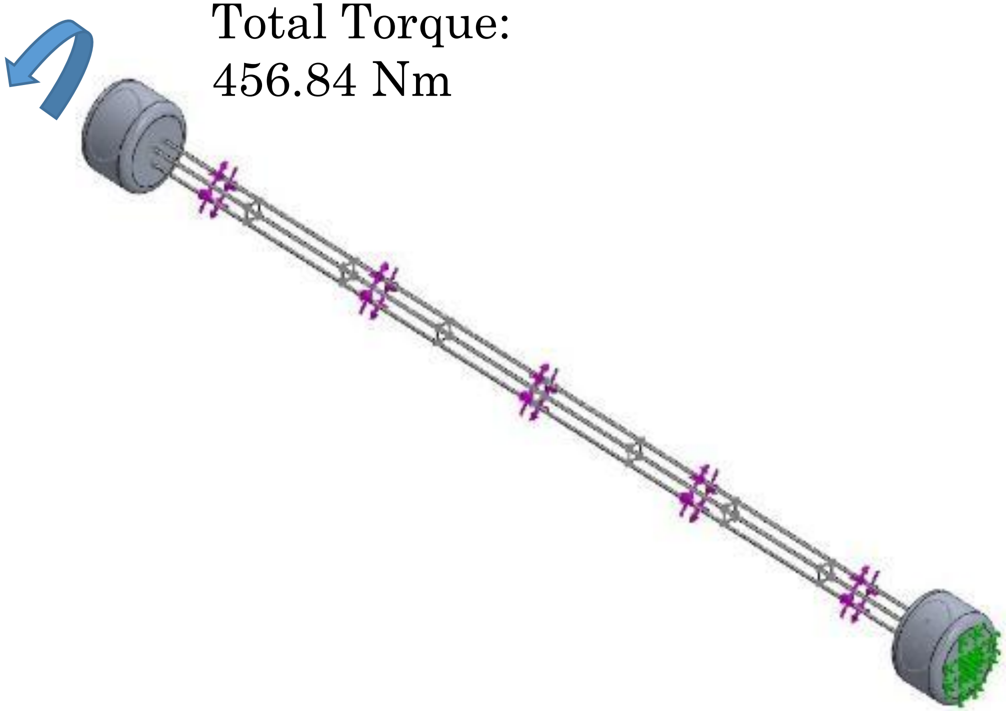
Bracing Trade Study

	BRC	Aluminum Rods	Carbon Fiber Rods
Total Mass (kg)	1.11	264.6	3.75
Tensile Strength (MPa)	2,400	310	4,620
Compressive Strength (MPa)	1,300	207	Unknown
Cost	Moderate-Expensive	Low	Expensive
Technological Readiness	Newer	Mature	Mature

- Chosen Design: Bi-Stable Reeled Composite (BRC)

Additional Bracing FEA





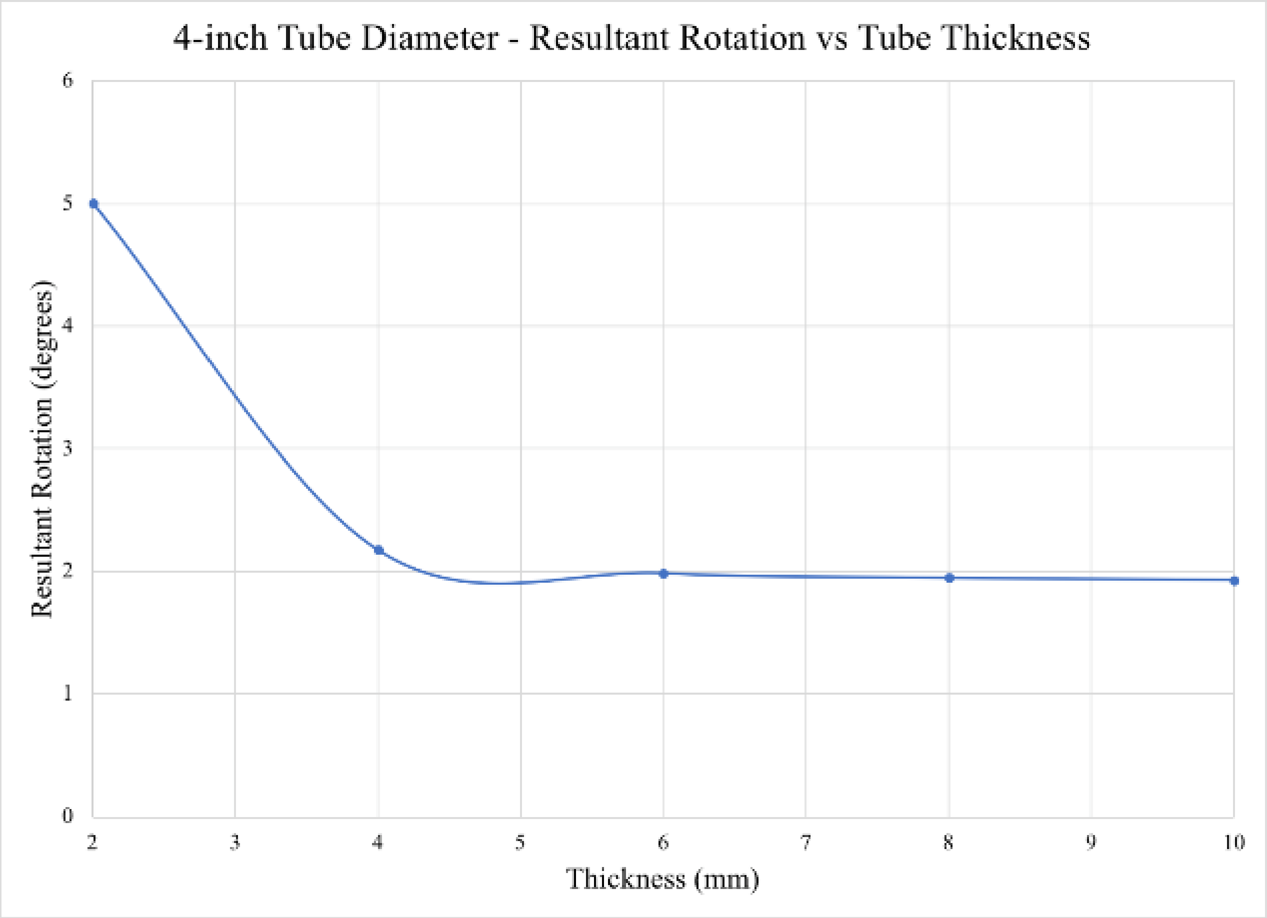
Total Torque:
456.84 Nm

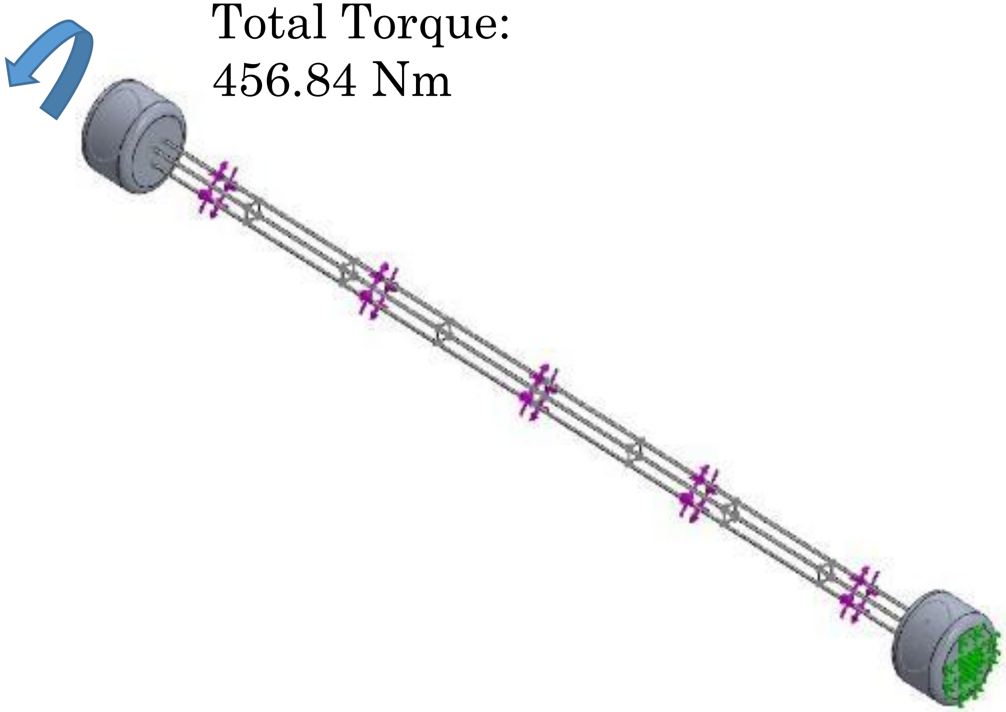
Fixed End

Nominal Brace Dimensions:
4-inch Tube Diameter
2-millimeter Tube Thickness

Chosen Number of Brace Sets: 7
Resultant Rotation: 5.01 degrees

7 Bracing Sets FEA





Total Torque:
456.84 Nm

Fixed End

Chosen Brace Dimensions:
4-inch Tube Diameter
6-millimeter Tube Thickness

Resultant Rotation:
1.99 degrees

Bracing and Supports Connection Trade Study

	Cross Tube Connector	Cross Tube Connector	T Tube Connector
			
Material	Steel	Plastic	Galvanized Steel
Mass	High	Low	High
Strength (MPa)	2,030	315	550
Cost	Low-Moderate	Low	Low-Moderate

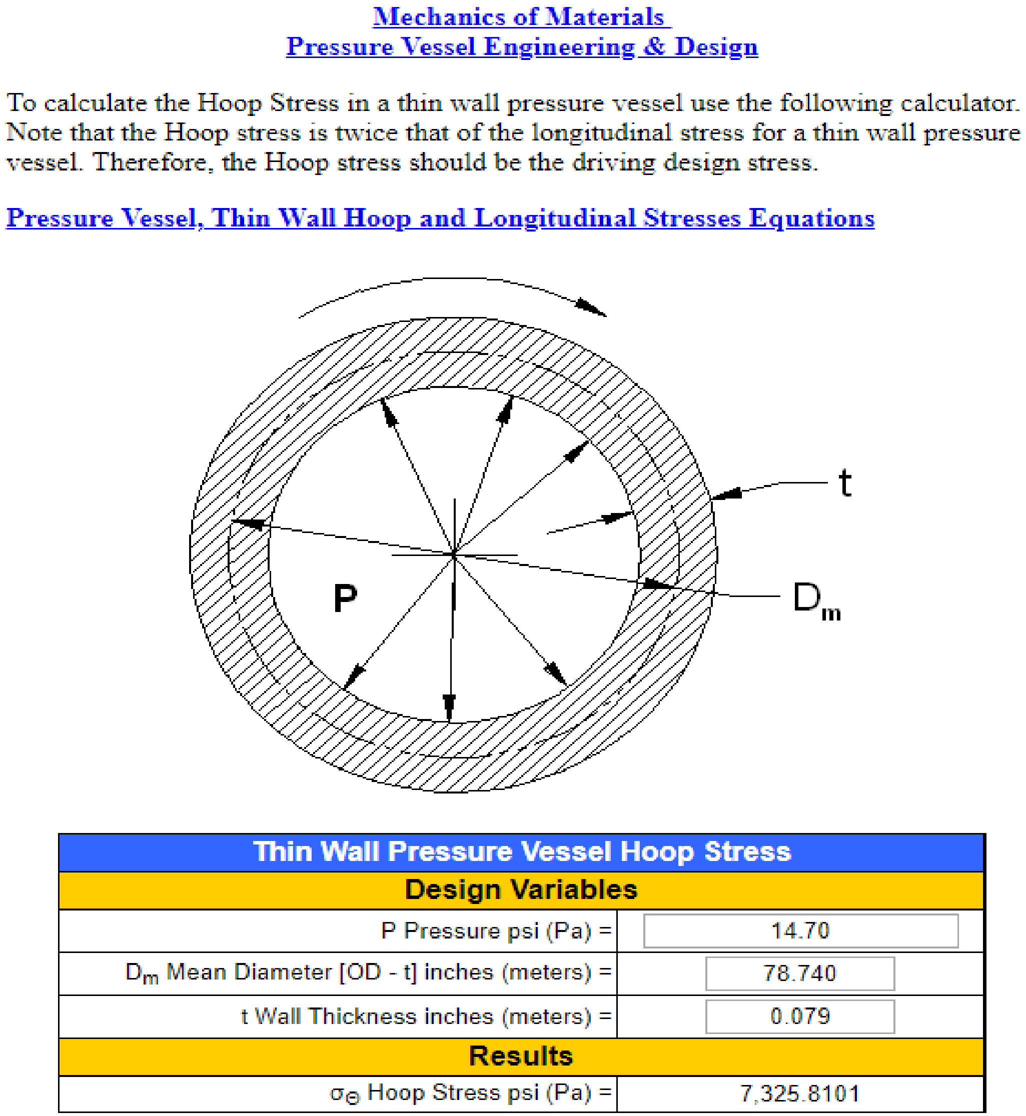
- Chosen Design: Cross Tube Connector - Plastic

Shroud Trade Study

	Kevlar	Carbon Nanotubes	Spectra Fiber
Strength	5 x stronger than steel	30 x stronger than steel	15 x stronger than steel
Mass	Light	Light	Light
UV Resistance	Some Degradation	Unknown	High Resistance
Temperature Sensitivity	Strengthens at low temperatures but weakens at high temperatures	Unknown	Brittle at -150°C and melts at 136°C
Cost	Moderate	Expensive	Moderate
Technological Readiness	Mature	Needs Development	New

- Chosen Design: Kevlar with UV Coating

Shroud Hoop Stress



Mechanics of Materials
Pressure Vessel Engineering & Design

To calculate the Hoop Stress in a thin wall pressure vessel use the following calculator. Note that the Hoop stress is twice that of the longitudinal stress for a thin wall pressure vessel. Therefore, the Hoop stress should be the driving design stress.

Pressure Vessel, Thin Wall Hoop and Longitudinal Stresses Equations

Thin Wall Pressure Vessel Hoop Stress	
Design Variables	
P Pressure psi (Pa) =	14.70
D_m Mean Diameter [OD - t] inches (meters) =	78.740
t Wall Thickness inches (meters) =	0.079
Results	
σ_Θ Hoop Stress psi (Pa) =	7,325.8101

Rotational Thrusters Trade Study

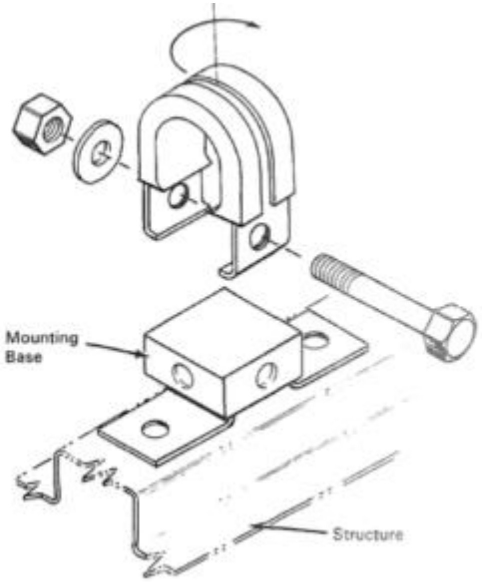
Thruster Type (Propellant)	Spin-Up Time (hr.)	Force per Thruster (N)	Total Mass (kg)	Power to Operate (kW)	Fuel Consumption (t)
Cold Gas (Nitrogen)	17	8.9	11,861	0.04	4.68
Hall Effect (Xenon)	28	5.4	1,268	204	0.99
Momentum Wheel	96	3.2	4,000	1,500	N/A
Chemical (Hydrazine)	6.7	22	2,796	0.082	2.80

- Chosen Design: Hall Effect

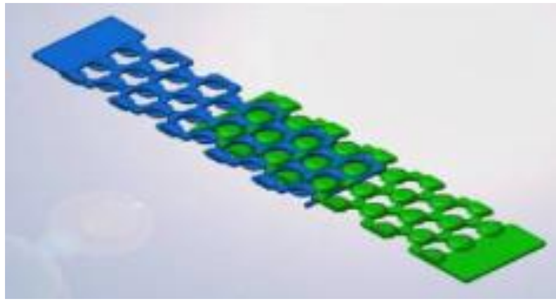
Connections Trade Study

	Velcro	**Xolox Strap**	**In-Line Cable Clamp**
Strength (psi)	Peel Strength: 1.2 Average Shear Strength: 14	Highly resistant to shear and tensile forces	Depends on clamp material
Supports	2 inch piece holds 175 lb.	Unknown	Depends on clamp material
Flexible	Yes	Yes	No
Technological Readiness	Mature	Needs Development	Mature
Cost	Inexpensive	Inexpensive	Inexpensive

- Chosen Design: Velcro



In-Line Clamp

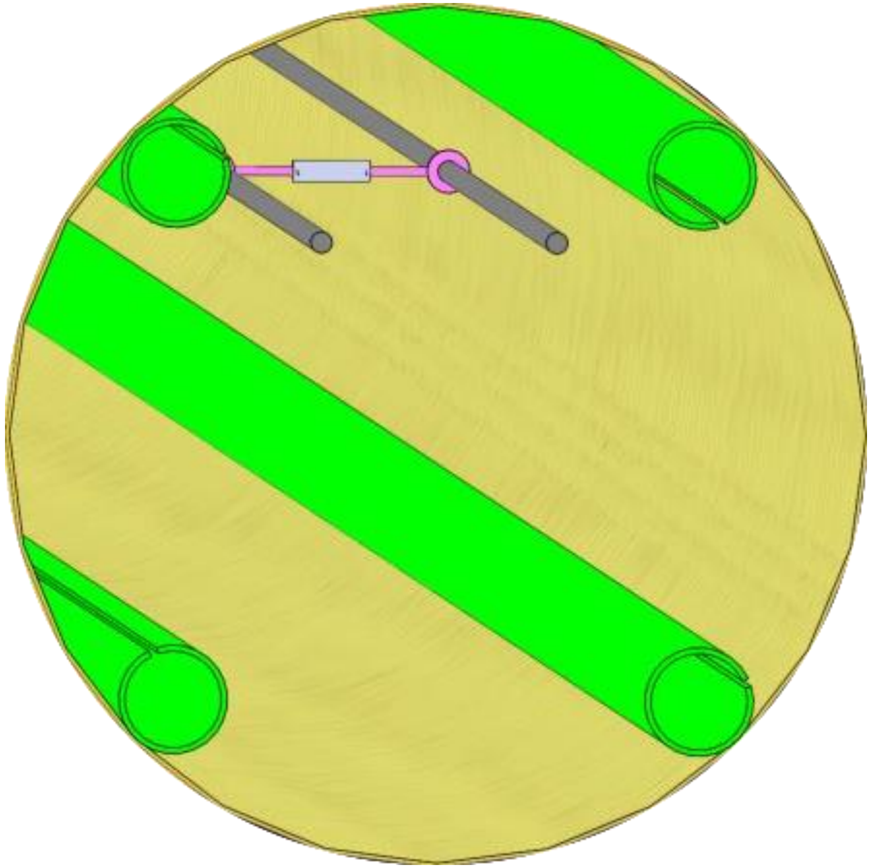


Xolox

Robotic System Trade Study

	Valkyrie R5	Spidernaut	Shadow Teleoperation Development System	ExoHand
Carrying Capacity (kg)	Unknown	45.4	10	Double the gripping power of human hand
Capabilities	Maintenance and inspection tasks	Carrying objects	Fine motor skills to make shaft connections	Fine motor skills to make shaft connections
Mass (kg)	136	272	28.9	Unknown
Size	1.88 meters tall	Exact dimensions unknown but it is fairly large	1.33 meter total reach	About the size of a human arm
Shaft Transit	Ladder System	Web	Similar to elevator shaft	Similar to elevator shaft
Power Required (kW)	1.8	3.6	0.5	Unknown
Battery Run Time (hr.)	6-10	Unknown	N/A Wired	N/A Wired
Cost	$2,000,000	High	Unknown	High
Technological Readiness	Needs Development	Needs Development	Ready	Needs Development

Expandable Shaft Robotic System Track



Expandable Shaft Cross-Sectional View with Robotic Track

Steel Cable Reel

Storage Organization System

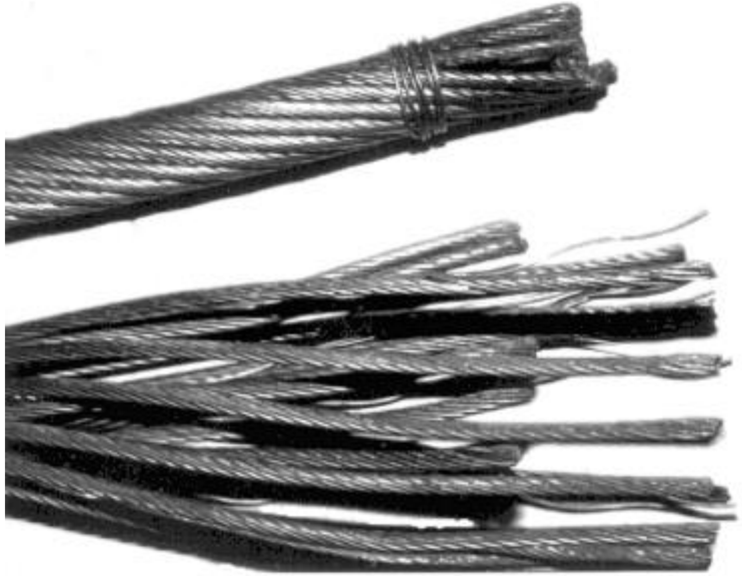
- Will use a robotic arm to scan and pick up objects from shelving
- Robotic arm will rotate around an axis in the center of the storage pod
- Software will have machine learning so the AI is continuously developing

Asteroid Impact

- Allow the asteroids/micrometeorites to pass through shroud
  - Robotic system would repair the damage
  - Possibility of major structural components inside the expandable shaft will be hit and catastrophically damaged
- Allow the asteroids/micrometeorites to strike but not penetrate
  - Prevents major structural components inside the expandable shaft from being hit
  - Possibility that the force of impact will throw the system off course or spin uncontrollably

Propulsion System and Central Hub Wiring

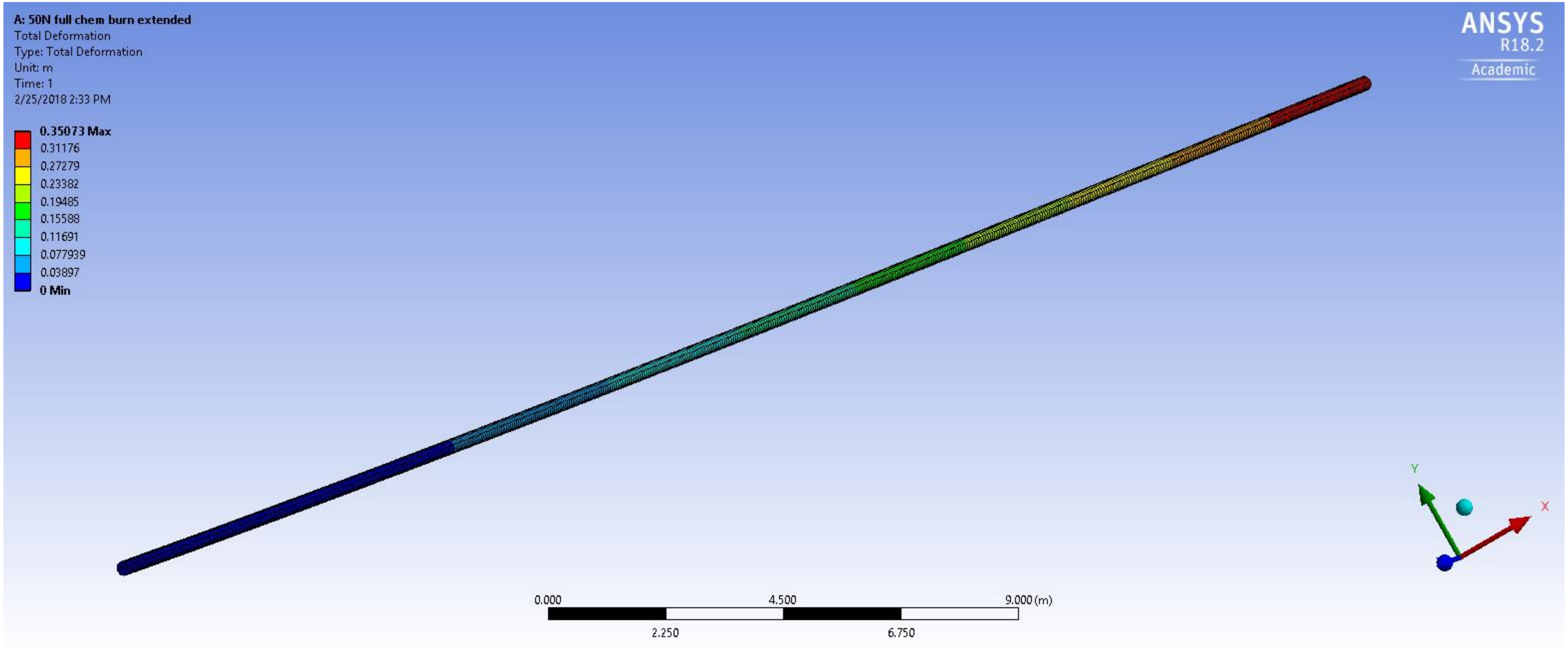
- Since the solar panels are connected to the propulsion system, the wiring will need to pass from that system to the central hub without getting caught in the rotation of the pod system
- Rotation resistant wiring is designed to resist spin or rotation so it will function well in this location



ANSYS Analysis – Titanium Support

50 N Chemical Thrust – 4 Supports

Deformation: 0.338 meters

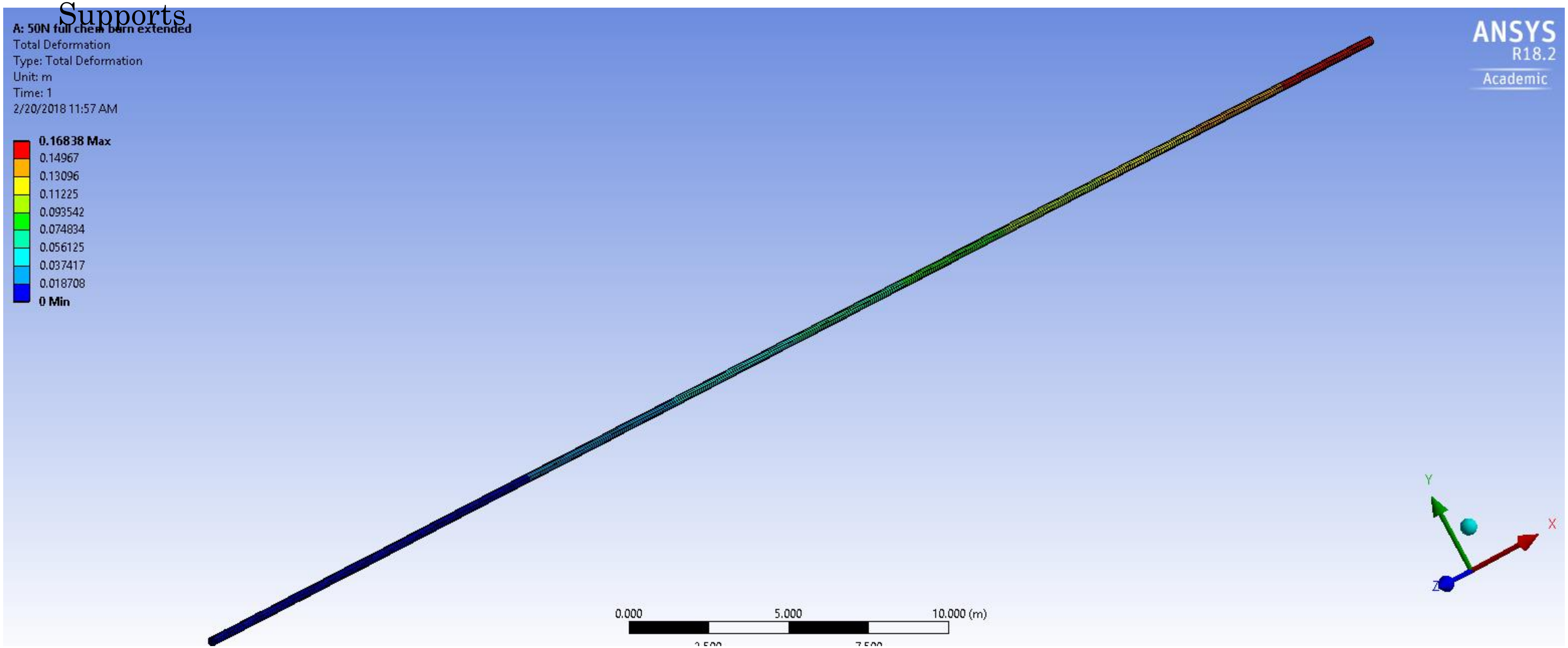


A: 50N full chem burn extended
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2/25/2018 2:33 PM

Preliminary ANSYS Support Analysis

50 N Chemical Thrust – Fully Contracted, 4 Supports

Deformation: 0.168 meters

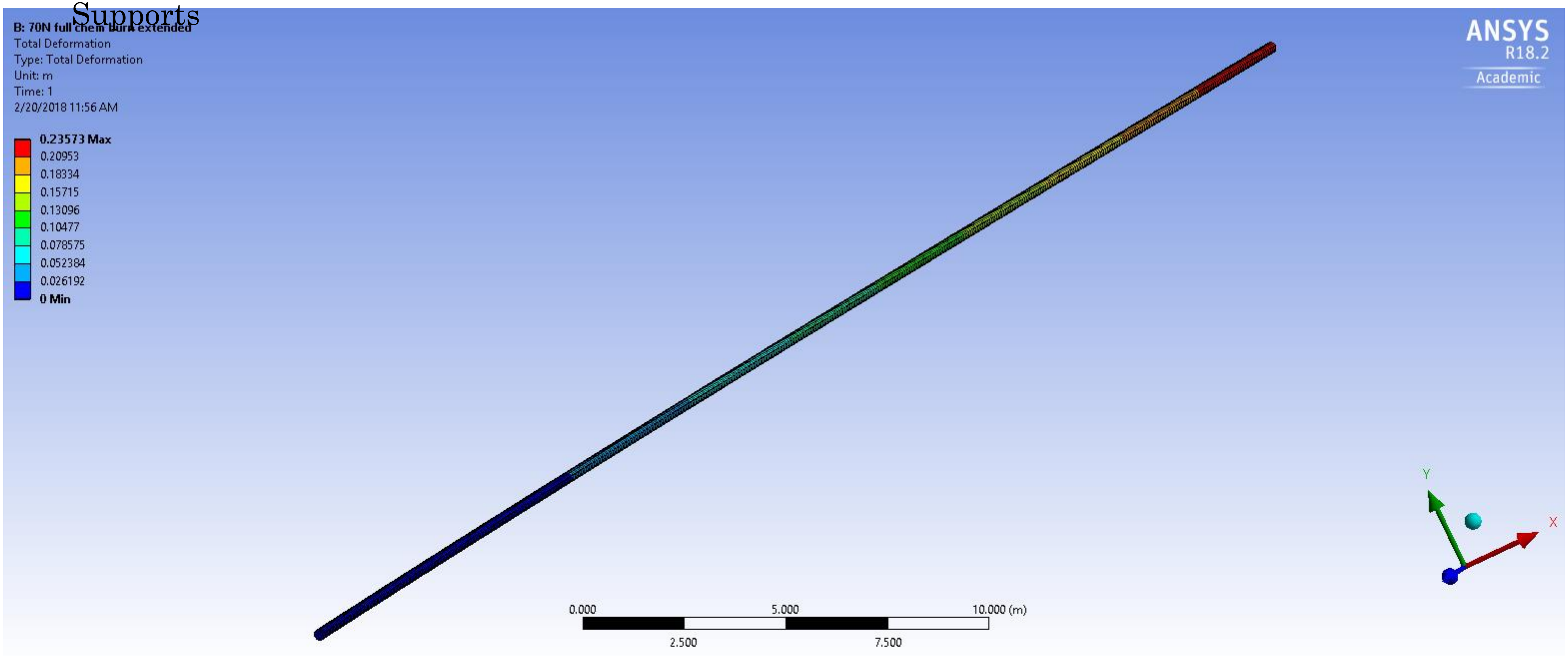


A: 50N full chem burn extended
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2/20/2018 11:57 AM

Preliminary ANSYS Support Analysis

70 N Chemical Thrust – Fully Extended, 4 Supports

Deformation: 0.0.235 meters

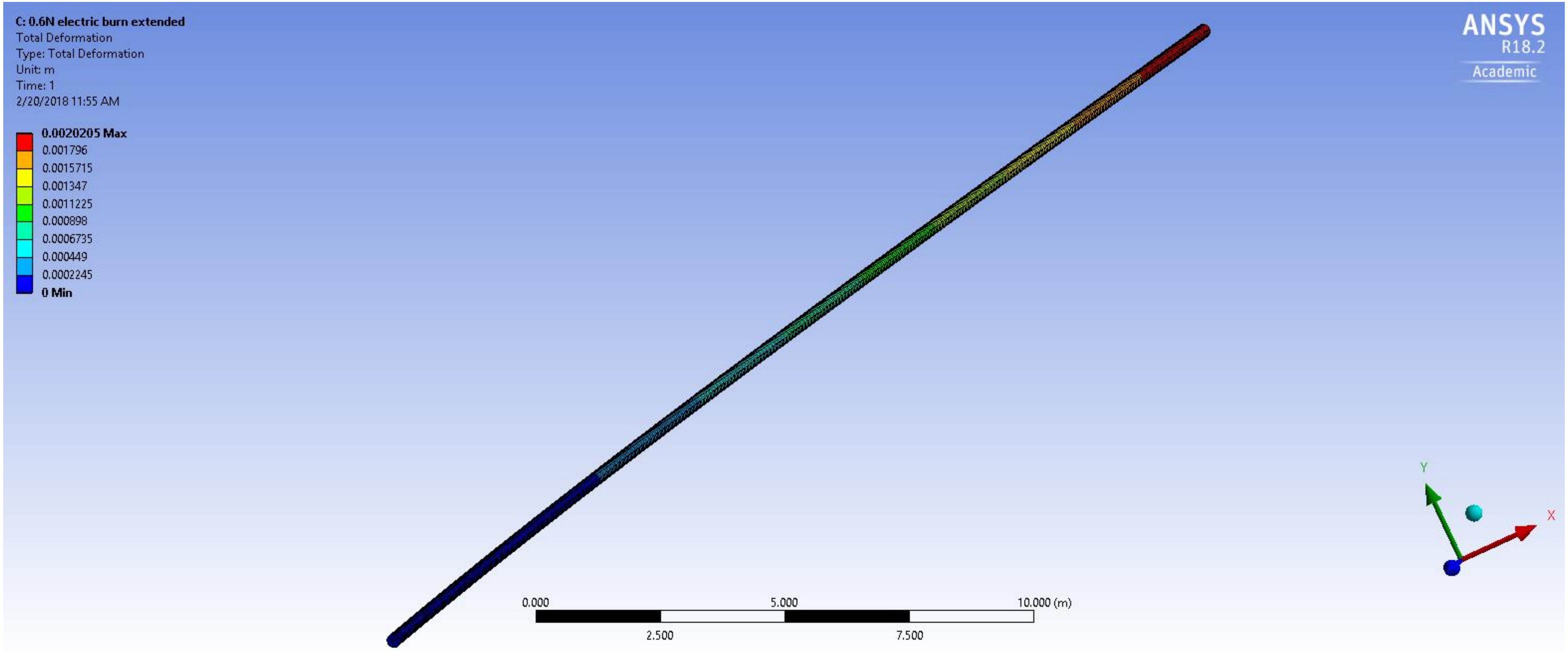


B: 70N full chem burn extended
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2/20/2018 11:56 AM

Preliminary ANSYS Support Analysis

0.6 N Electric Thrust – Fully Extended, 4 Supports

Deformation: 0.0017 meters

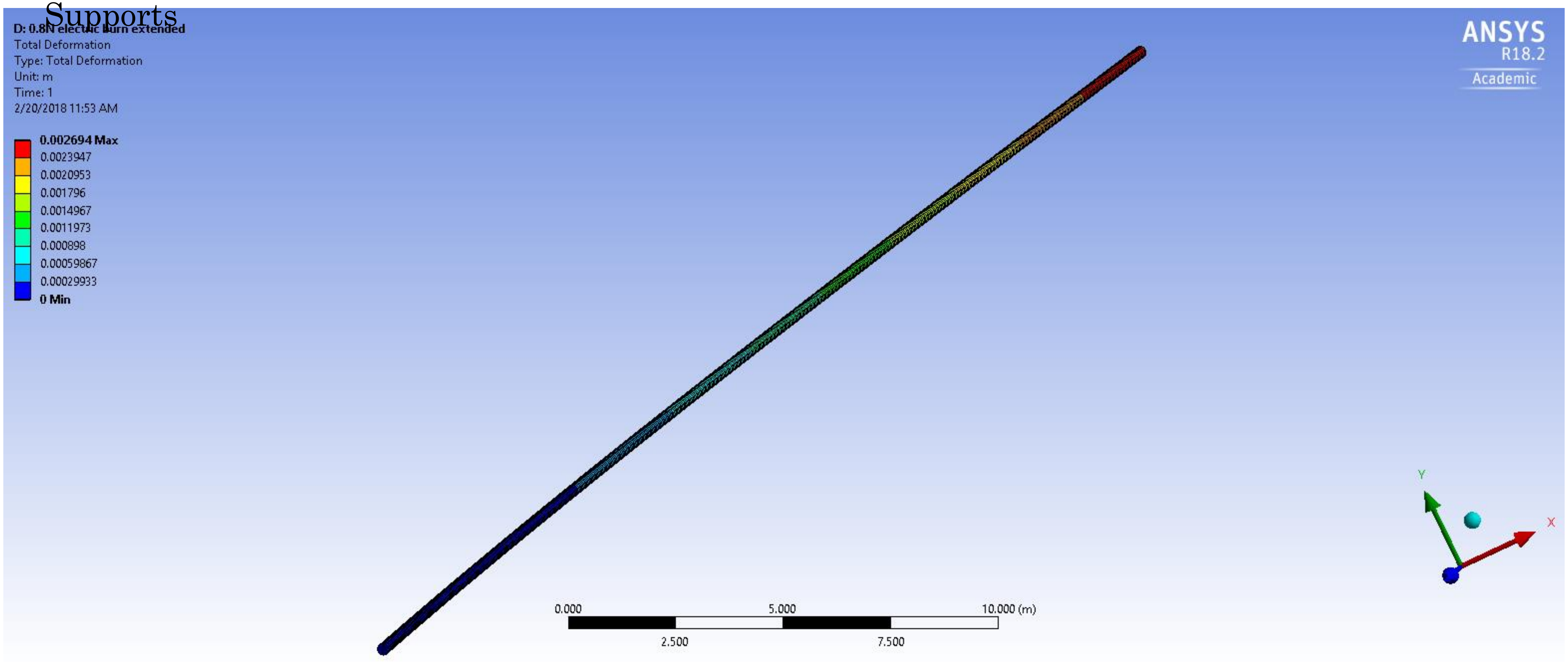


C: 0.6N electric burn extended
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2/20/2018 11:55 AM

Preliminary ANSYS Support Analysis

0.8 N Electric Thrust – Fully Extended, 4 Supports

Deformation: 0.0027 meters



Preliminary ANSYS Support Analysis Conclusion

- The system should not be launched fully extended since the chemical thrust will cause too much deformation in the system
- The system must launch from the hammerhead configuration to withstand chemical thrust
- The system will can withstand being fully extended during the electric thrust

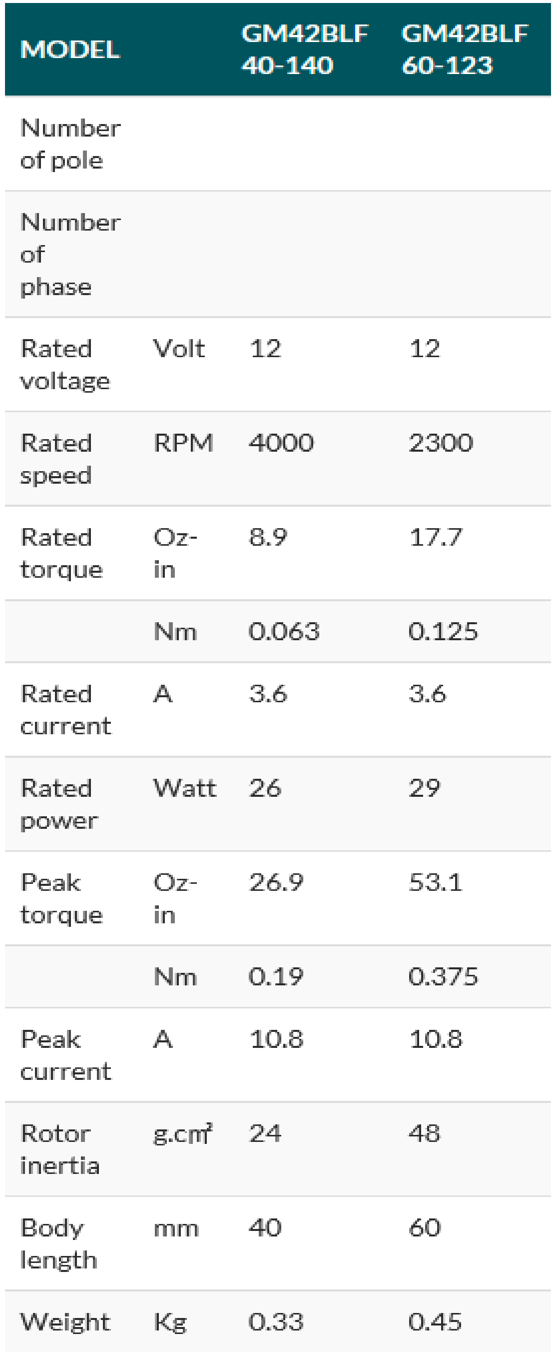
Expansion Motor Calculations

$$x - x_0 = V_0 t + 0.5at^2$$
$$84.6m = 0.5 * a * (1200sec)^2$$
$$a = 0.0001175m/s$$

$$F = ma = (46{,}000kg)\left(\frac{0.0001175m}{s}\right) = 5.405N$$

$$P = \frac{Fd}{t} = \frac{5.405N * 0.05}{1200sec} = 0.000225W$$

Expansion Motor Specifications



MODEL		GM42BLF 40-140	GM42BLF 60-123
Number of pole			
Number of phase			
Rated voltage	Volt	12	12
Rated speed	RPM	4000	2300
Rated torque	Oz-in	8.9	17.7
	Nm	0.063	0.125
Rated current	A	3.6	3.6
Rated power	Watt	26	29
Peak torque	Oz-in	26.9	53.1
	Nm	0.19	0.375
Peak current	A	10.8	10.8
Rotor inertia	g.cm²	24	48
Body length	mm	40	60
Weight	Kg	0.33	0.45

Shroud Thermal Differential

- Sun directly hitting the shroud with worst-case scenario thermal properties:

$$q_{net} = 0$$

$$\alpha = 0.95$$

$$\varepsilon = 0.9$$

$$G_{SolarMax} = 1{,}373$$

$$\sigma_{StefanBoltzman} = 5.67 * 10^{-8}$$

$$T_{SMax} = \left[\frac{\alpha * G_{SolarMax}}{\varepsilon * \sigma_{StefanBoltzman}}\right]^{0.25}$$

$$T_{SMax} = 399.85\ K$$

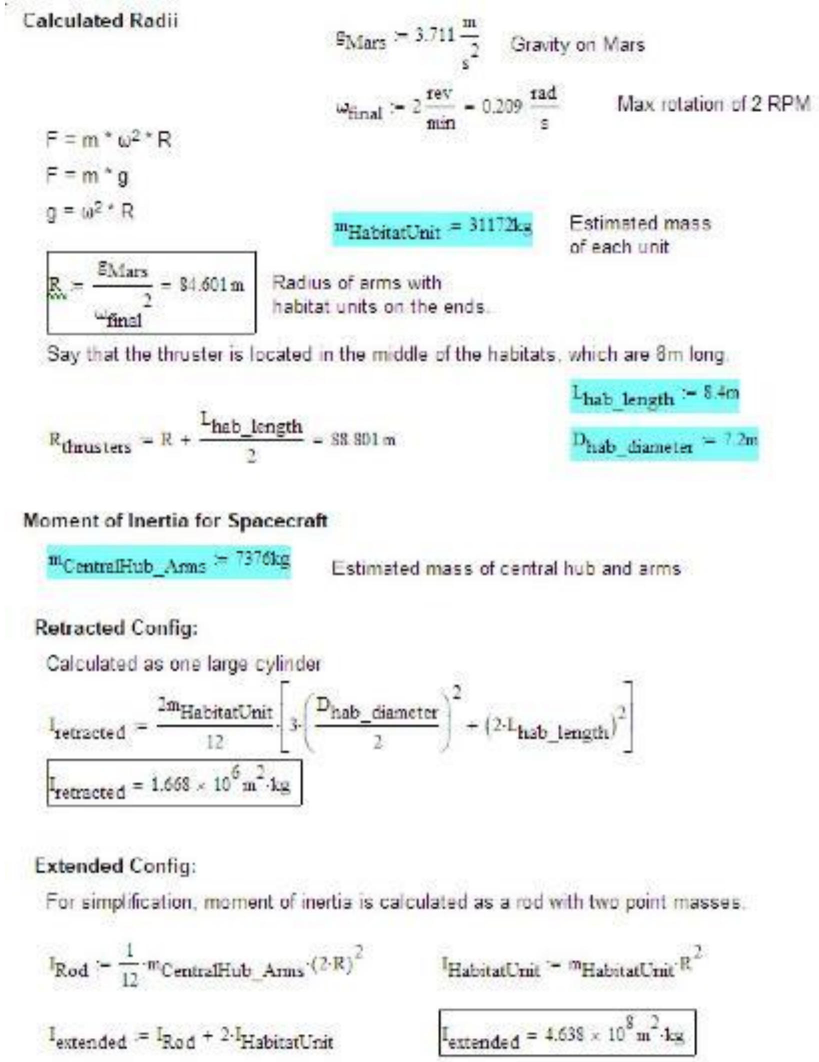
Hall Effect Thrusters Trade Study

Thruster Name	Spin-Up Time (hr.)	Force per Thruster (N)	Total Mass (kg)	Power to Operate (kW)
X3	28	5.4	1,268	204
HermeS TDU-1	250	0.6	699	25
HiVHAc	760	0.2	547	7.8

In an effort to further optimize for weight, Hall Thrusters of varying sizes with different spin-up times were analyzed.

- Chosen Design: X3

Thrusters Calculations



Calculated Radii

$g_{Mars} := 3.711 \frac{m}{s^2}$ Gravity on Mars

$\omega_{final} := 2 \frac{rev}{min} = 0.209 \frac{rad}{s}$ Max rotation of 2 RPM

F = m * ω² * R

F = m * g

g = ω² * R

$m_{HabitatUnit} = 31172kg$ Estimated mass of each unit

$\boxed{R := \frac{g_{Mars}}{\omega_{final}^2} = 84.601\,m}$ Radius of arms with habitat units on the ends.

Say that the thruster is located in the middle of the habitats, which are 8m long.

$L_{hab\_length} := 8.4m$

$D_{hab\_diameter} := 7.2m$

$R_{thrusters} := R + \frac{L_{hab\_length}}{2} = 88.801\,m$

Moment of Inertia for Spacecraft

$m_{CentralHub\_Arms} := 7376kg$ Estimated mass of central hub and arms

Retracted Config:

Calculated as one large cylinder

$I_{retracted} := \frac{2m_{HabitatUnit}}{12} \cdot \left[3 \cdot \left(\frac{D_{hab\_diameter}}{2}\right)^2 + (2 \cdot L_{hab\_length})^2\right]$

$\boxed{I_{retracted} = 1.668 \times 10^6\,m^2 \cdot kg}$

Extended Config:

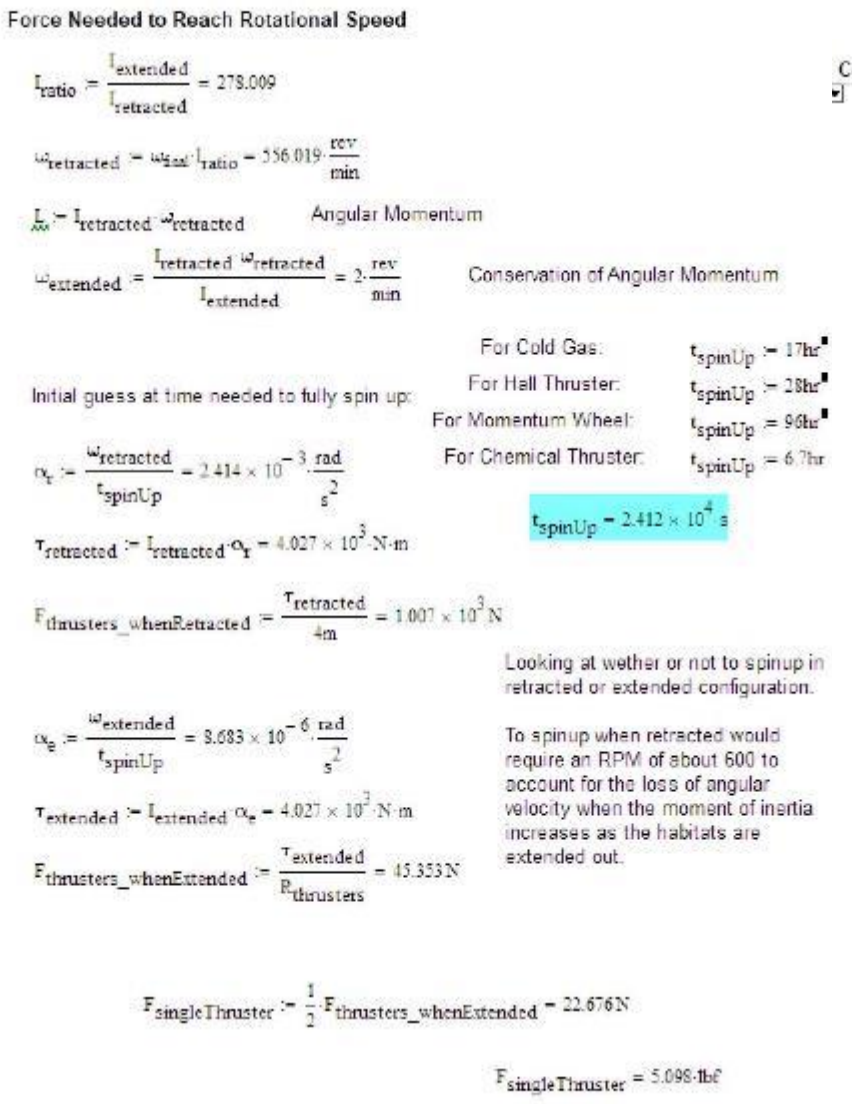
For simplification, moment of inertia is calculated as a rod with two point masses.

$I_{Rod} := \frac{1}{12} \cdot m_{CentralHub\_Arms} \cdot (2 \cdot R)^2$

$I_{HabitatUnit} := m_{HabitatUnit} \cdot R^2$

$I_{extended} := I_{Rod} + 2 \cdot I_{HabitatUnit}$

$\boxed{I_{extended} = 4.638 \times 10^8\,m^2 \cdot kg}$



Force Needed to Reach Rotational Speed

$I_{ratio} := \frac{I_{extended}}{I_{retracted}} = 278.009$

$\omega_{retracted} := \omega_{final} \cdot I_{ratio} = 556.019 \cdot \frac{rev}{min}$

$L := I_{retracted} \cdot \omega_{retracted}$ Angular Momentum

$\omega_{extended} := \frac{I_{retracted} \cdot \omega_{retracted}}{I_{extended}} = 2 \cdot \frac{rev}{min}$ Conservation of Angular Momentum

Initial guess at time needed to fully spin up:

For Cold Gas: $t_{spinUp} := 17hr$

For Hall Thruster: $t_{spinUp} := 28hr$

For Momentum Wheel: $t_{spinUp} = 96hr$

For Chemical Thruster: $t_{spinUp} = 6.7hr$

$t_{spinUp} = 2.412 \times 10^4\,s$

$\alpha_r := \frac{\omega_{retracted}}{t_{spinUp}} = 2.414 \times 10^{-3} \cdot \frac{rad}{s^2}$

$\tau_{retracted} := I_{retracted} \cdot \alpha_r = 4.027 \times 10^3 \cdot N \cdot m$

$F_{thrusters\_whenRetracted} := \frac{\tau_{retracted}}{4m} = 1.007 \times 10^3\,N$

Looking at wether or not to spinup in retracted or extended configuration.

$\alpha_e := \frac{\omega_{extended}}{t_{spinUp}} = 8.683 \times 10^{-6} \cdot \frac{rad}{s^2}$

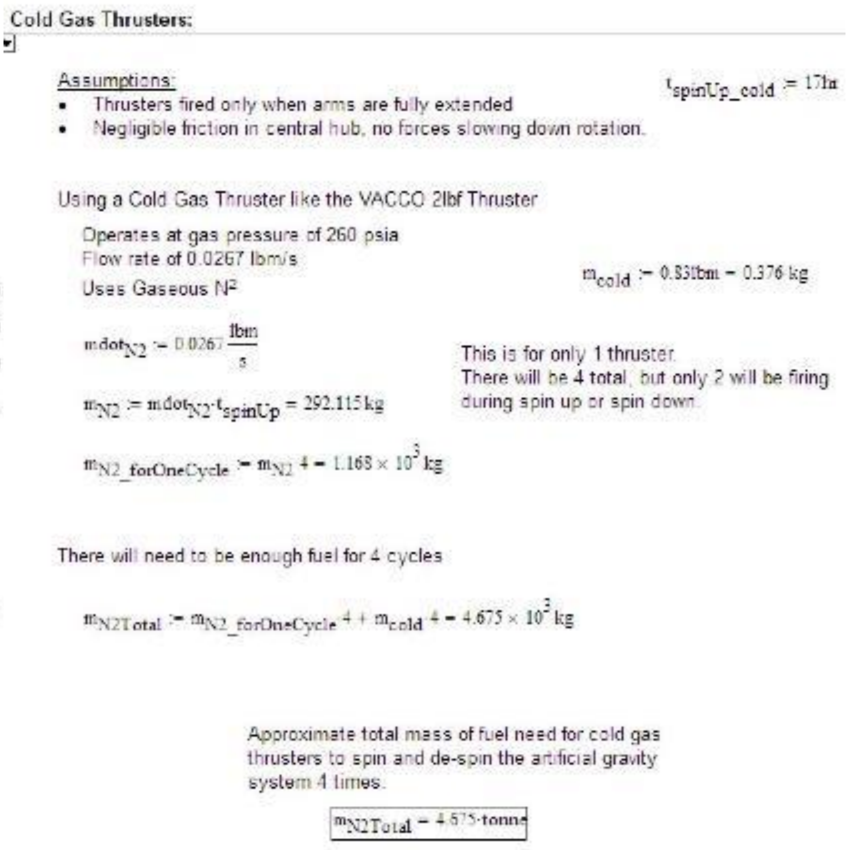
$\tau_{extended} := I_{extended} \cdot \alpha_e = 4.027 \times 10^3 \cdot N \cdot m$

$F_{thrusters\_whenExtended} := \frac{\tau_{extended}}{R_{thrusters}} = 45.353\,N$

To spinup when retracted would require an RPM of about 600 to account for the loss of angular velocity when the moment of inertia increases as the habitats are extended out.

$F_{singleThruster} := \frac{1}{2} \cdot F_{thrusters\_whenExtended} = 22.676\,N$

$F_{singleThruster} = 5.098 \cdot lbf$



Cold Gas Thrusters:

Assumptions:
- Thrusters fired only when arms are fully extended
- Negligible friction in central hub, no forces slowing down rotation.

$t_{spinUp\_cold} := 17hr$

Using a Cold Gas Thruster like the VACCO 2lbf Thruster

Operates at gas pressure of 260 psia
Flow rate of 0.0267 lbm/s
Uses Gaseous N²

$m_{cold} := 0.83lbm = 0.376\,kg$

$mdot_{N2} := 0.0267 \frac{lbm}{s}$

$m_{N2} := mdot_{N2} \cdot t_{spinUp} = 292.115\,kg$

This is for only 1 thruster.
There will be 4 total, but only 2 will be firing during spin up or spin down.

$m_{N2\_forOneCycle} := m_{N2} \cdot 4 = 1.168 \times 10^3\,kg$

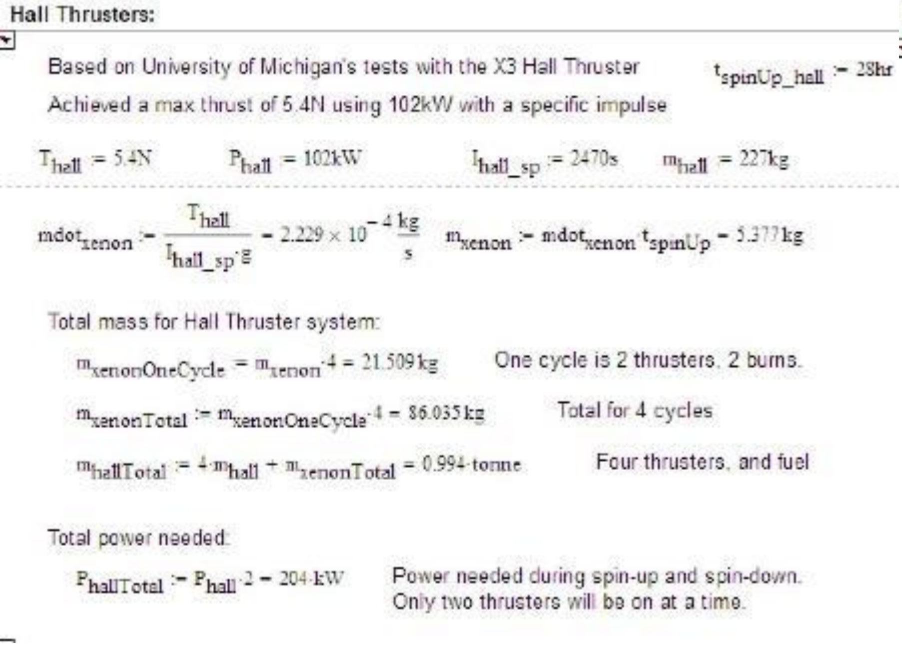
There will need to be enough fuel for 4 cycles

$m_{N2Total} := m_{N2\_forOneCycle} \cdot 4 + m_{cold} \cdot 4 = 4.675 \times 10^3\,kg$

Approximate total mass of fuel need for cold gas thrusters to spin and de-spin the artificial gravity system 4 times.

$\boxed{m_{N2Total} = 4.675 \cdot tonne}$

Thrusters Calculations Continued



Hall Thrusters:

Based on University of Michigan's tests with the X3 Hall Thruster
Achieved a max thrust of 5.4N using 102kW with a specific impulse

$t_{spinUp\_hall} := 28hr$

$T_{hall} := 5.4N$ $P_{hall} := 102kW$ $I_{hall\_sp} := 2470s$ $m_{hall} := 227kg$

$$mdot_{xenon} := \frac{T_{hall}}{I_{hall\_sp} \cdot g} = 2.229 \times 10^{-4} \frac{kg}{s} \qquad m_{xenon} := mdot_{xenon} \cdot t_{spinUp} = 5.377kg$$

Total mass for Hall Thruster system:

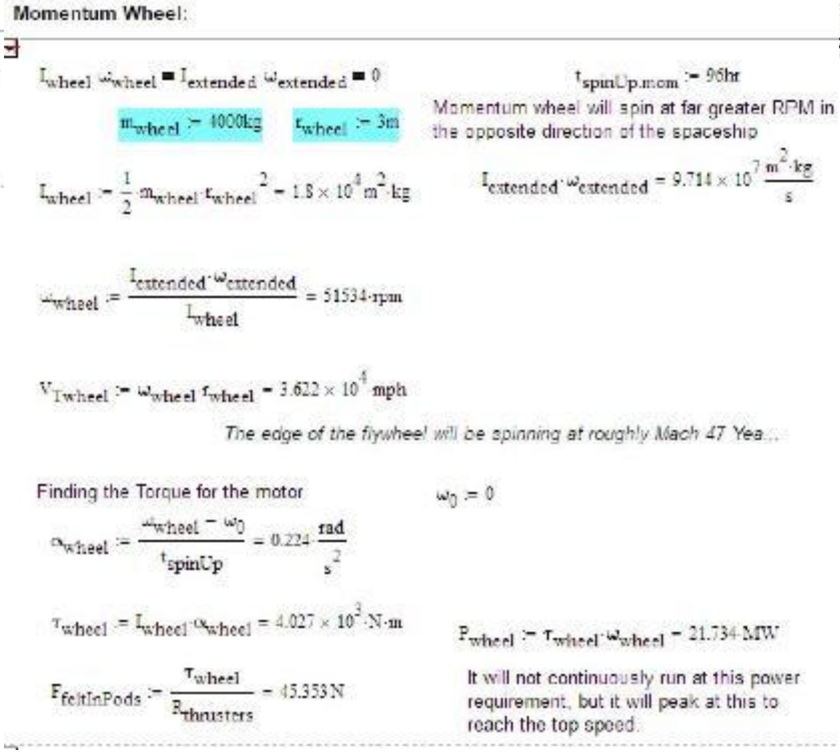
$m_{xenonOneCycle} := m_{xenon} \cdot 4 = 21.509kg$ One cycle is 2 thrusters, 2 burns.

$m_{xenonTotal} := m_{xenonOneCycle} \cdot 4 = 86.035kg$ Total for 4 cycles

$m_{hallTotal} := 4 \cdot m_{hall} + m_{xenonTotal} = 0.994 \cdot tonne$ Four thrusters, and fuel

Total power needed:

$P_{hallTotal} := P_{hall} \cdot 2 = 204 \cdot kW$ Power needed during spin-up and spin-down.
Only two thrusters will be on at a time.



Momentum Wheel:

$I_{wheel} \cdot \omega_{wheel} = I_{extended} \cdot \omega_{extended} = 0$

$t_{spinUp.mom} := 96hr$

$m_{wheel} := 4000kg$ $r_{wheel} := 3m$

Momentum wheel will spin at far greater RPM in the opposite direction of the spaceship

$$I_{wheel} := \frac{1}{2} m_{wheel} \cdot r_{wheel}^{2} = 1.8 \times 10^{4} m^{2} \cdot kg \qquad I_{extended} \cdot \omega_{extended} = 9.714 \times 10^{7} \frac{m^{2} \cdot kg}{s}$$

$$\omega_{wheel} := \frac{I_{extended} \cdot \omega_{extended}}{I_{wheel}} = 51534 \cdot rpm$$

$V_{Twheel} := \omega_{wheel} \cdot r_{wheel} = 3.622 \times 10^{4} mph$

The edge of the flywheel will be spinning at roughly Mach 47 Yea...

Finding the Torque for the motor $\omega_0 := 0$

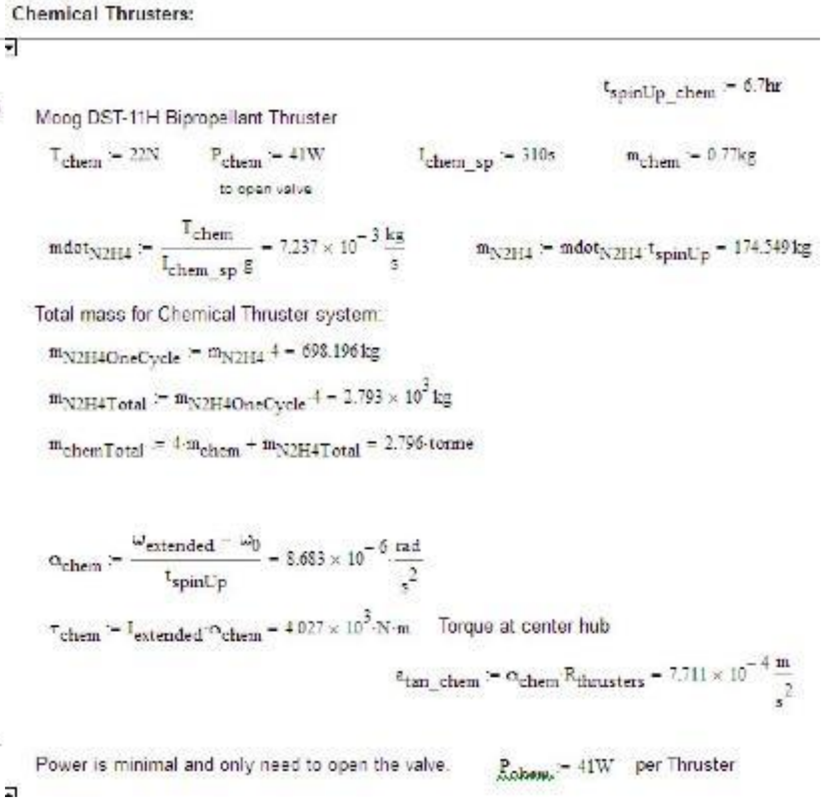
$$\alpha_{wheel} := \frac{\omega_{wheel} - \omega_0}{t_{spinUp}} = 0.224 \frac{rad}{s^{2}}$$

$\tau_{wheel} := I_{wheel} \cdot \alpha_{wheel} = 4.027 \times 10^{3} \cdot N \cdot m$

$P_{wheel} := \tau_{wheel} \cdot \omega_{wheel} = 21.734 \cdot MW$

$$F_{feltInPods} := \frac{\tau_{wheel}}{R_{thrusters}} = 45.353N$$

It will not continuously run at this power requirement, but it will peak at this to reach the top speed.



Chemical Thrusters:

$t_{spinUp\_chem} := 6.7hr$

Moog DST-11H Bipropellant Thruster

$T_{chem} := 22N$ $P_{chem} := 41W$ to open valve $I_{chem\_sp} := 310s$ $m_{chem} := 0.77kg$

$$mdot_{N2H4} := \frac{T_{chem}}{I_{chem\_sp} \cdot g} = 7.237 \times 10^{-3} \frac{kg}{s} \qquad m_{N2H4} := mdot_{N2H4} \cdot t_{spinUp} = 174.549kg$$

Total mass for Chemical Thruster system:

$m_{N2H4OneCycle} := m_{N2H4} \cdot 4 = 698.196kg$

$m_{N2H4Total} := m_{N2H4OneCycle} \cdot 4 = 2.793 \times 10^{3} kg$

$m_{chemTotal} := 4 \cdot m_{chem} + m_{N2H4Total} = 2.796 \cdot tonne$

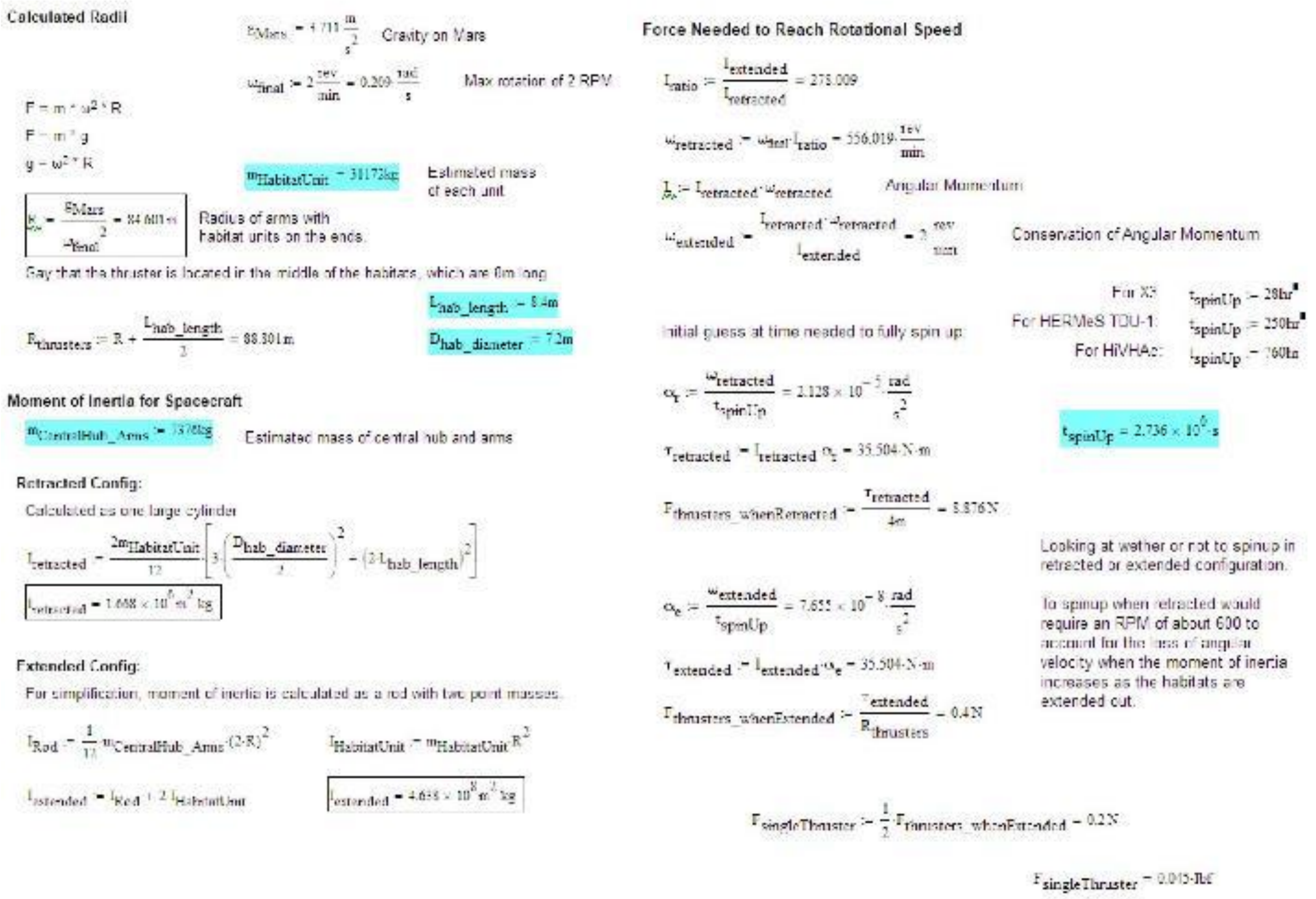
$$\alpha_{chem} := \frac{\omega_{extended} - \omega_0}{t_{spinUp}} = 8.683 \times 10^{-6} \cdot \frac{rad}{s^{2}}$$

$\tau_{chem} := I_{extended} \cdot \alpha_{chem} = 4.027 \times 10^{3} \cdot N \cdot m$ Torque at center hub

$$a_{tan\_chem} := \alpha_{chem} \cdot R_{thrusters} = 7.711 \times 10^{-4} \frac{m}{s^{2}}$$

Power is minimal and only need to open the valve. $P_{chem} := 41W$ per Thruster

Hall Thrusters Calculations



Calculated Radii

$g_{Mars} := 3.711\frac{m}{s^2}$ Gravity on Mars

$\omega_{final} := 2\frac{rev}{min} = 0.209\frac{rad}{s}$ Max rotation of 2 RPM

$F = m \cdot \omega^2 \cdot R$

$F = m \cdot g$

$g = \omega^2 \cdot R$

$m_{HabitatUnit} := 31172kg$ Estimated mass of each unit

$\boxed{R := \frac{g_{Mars}}{\omega_{final}^2} = 84.801 m}$ Radius of arms with habitat units on the ends.

Say that the thruster is located in the middle of the habitats, which are 8m long

$L_{hab\_length} := 8.4m$

$D_{hab\_diameter} := 7.2m$

$R_{thrusters} := R + \frac{L_{hab\_length}}{2} = 88.301 m$

Moment of Inertia for Spacecraft

$m_{CentralHub\_Arms} := 7378kg$ Estimated mass of central hub and arms

Retracted Config:

Calculated as one large cylinder

$I_{retracted} := \frac{2m_{HabitatUnit}}{12}\left[3\left(\frac{D_{hab\_diameter}}{2}\right)^2 + (2 \cdot L_{hab\_length})^2\right]$

$\boxed{I_{retracted} = 1.688 \times 10^6 m^2 \cdot kg}$

Extended Config:

For simplification, moment of inertia is calculated as a rod with two point masses.

$I_{Rod} := \frac{1}{12} m_{CentralHub\_Arms} \cdot (2 \cdot R)^2$

$I_{HabitatUnit} := m_{HabitatUnit} \cdot R^2$

$I_{extended} := I_{Rod} + 2 \cdot I_{HabitatUnit}$

$\boxed{I_{extended} = 4.643 \times 10^8 m^2 \cdot kg}$

Force Needed to Reach Rotational Speed

$I_{ratio} := \frac{I_{extended}}{I_{retracted}} = 275.009$

$\omega_{retracted} := \omega_{final} \cdot I_{ratio} = 556.019 \cdot \frac{rev}{min}$

$L := I_{retracted} \cdot \omega_{retracted}$ Angular Momentum

$\omega_{extended} := \frac{I_{retracted} \cdot \omega_{retracted}}{I_{extended}} = 2\frac{rev}{min}$ Conservation of Angular Momentum

For X3: $t_{spinUp} := 28hr$

For HERMeS TDU-1: $t_{spinUp} := 250hr$

For HiVHAc: $t_{spinUp} := 760hr$

Initial guess at time needed to fully spin up:

$\alpha_r := \frac{\omega_{retracted}}{t_{spinUp}} = 2.128 \times 10^{-5} \cdot \frac{rad}{s^2}$

$t_{spinUp} = 2.736 \times 10^6 \cdot s$

$\tau_{retracted} := I_{retracted} \cdot \alpha_r = 35.504 \cdot N \cdot m$

$F_{thrusters\_whenRetracted} := \frac{\tau_{retracted}}{4m} = 8.876N$

Looking at wether or not to spinup in retracted or extended configuration.

To spinup when retracted would require an RPM of about 600 to account for the loss of angular velocity when the moment of inertia increases as the habitats are extended out.

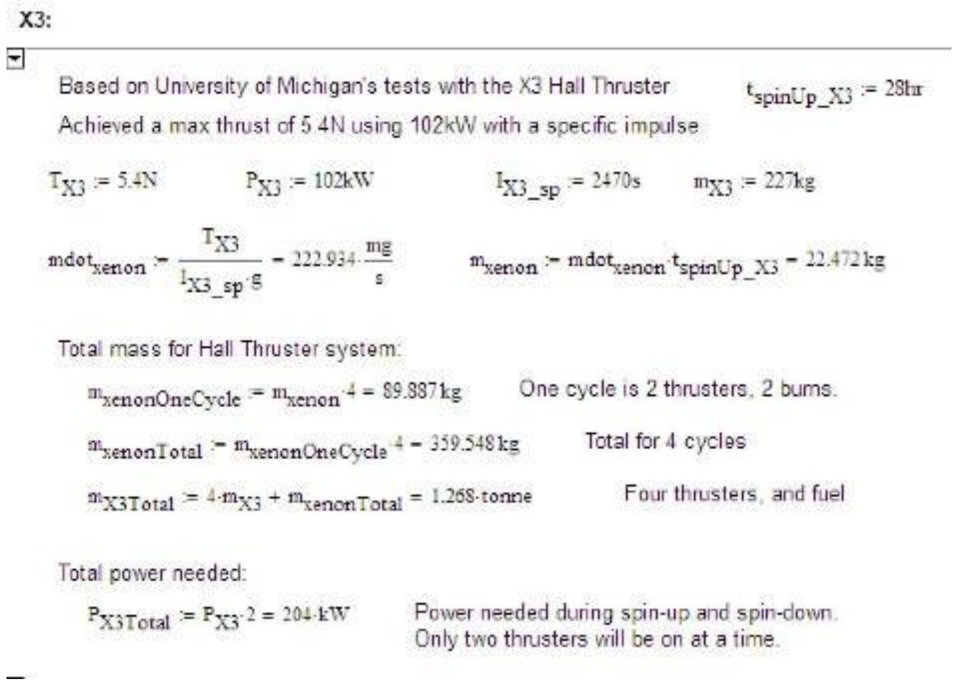
$\alpha_e := \frac{\omega_{extended}}{t_{spinUp}} = 7.655 \times 10^{-8} \cdot \frac{rad}{s^2}$

$\tau_{extended} := I_{extended} \cdot \alpha_e = 35.504 \cdot N \cdot m$

$F_{thrusters\_whenExtended} := \frac{\tau_{extended}}{R_{thrusters}} = 0.4N$

$F_{singleThruster} := \frac{1}{2} \cdot F_{thrusters\_whenExtended} = 0.2N$

$F_{singleThruster} = 0.045 \cdot lbf$



X3:

Based on University of Michigan's tests with the X3 Hall Thruster

Achieved a max thrust of 5.4N using 102kW with a specific impulse

$t_{spinUp\_X3} := 28hr$

$T_{X3} := 5.4N$ $P_{X3} := 102kW$ $I_{X3\_sp} := 2470s$ $m_{X3} := 227kg$

$mdot_{xenon} := \frac{T_{X3}}{I_{X3\_sp} \cdot g} = 222.934 \cdot \frac{mg}{s}$

$m_{xenon} := mdot_{xenon} \cdot t_{spinUp\_X3} = 22.472 kg$

Total mass for Hall Thruster system:

$m_{xenonOneCycle} := m_{xenon} \cdot 4 = 89.887 kg$ One cycle is 2 thrusters, 2 burns.

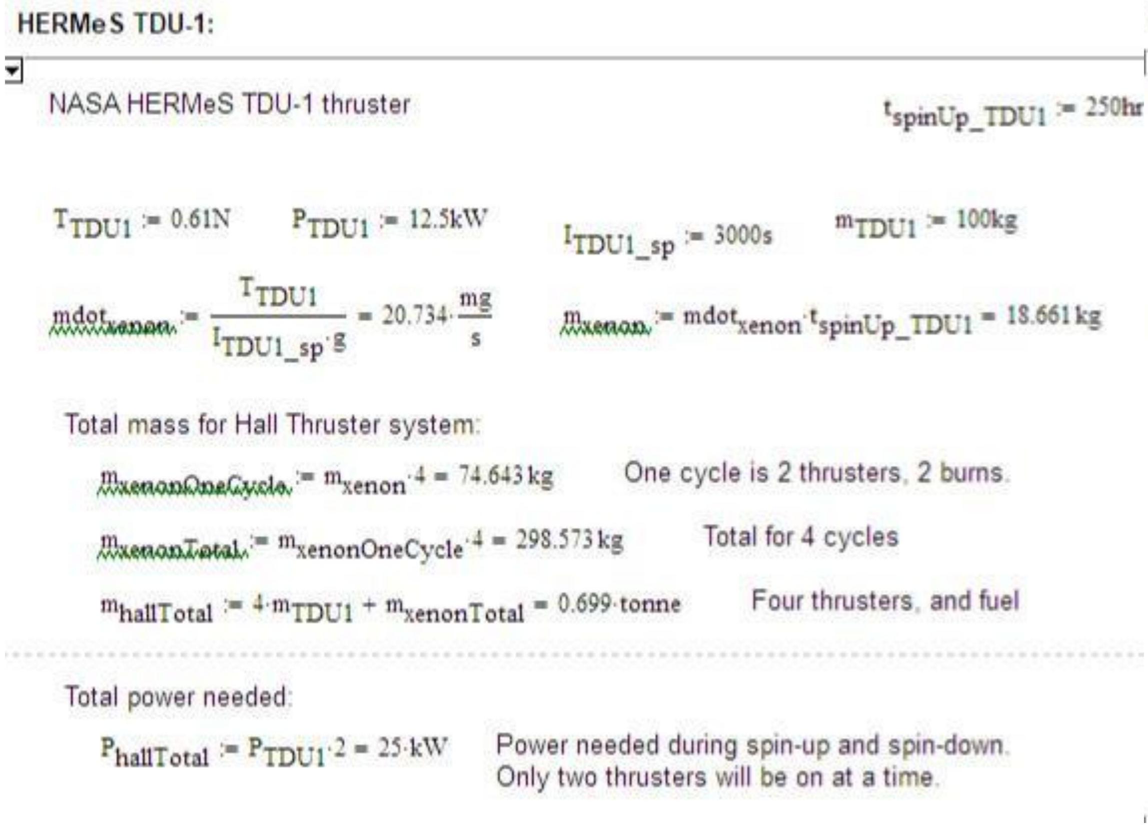
$m_{xenonTotal} := m_{xenonOneCycle} \cdot 4 = 359.548 kg$ Total for 4 cycles

$m_{X3Total} := 4 \cdot m_{X3} + m_{xenonTotal} = 1.268 \cdot tonne$ Four thrusters, and fuel

Total power needed:

$P_{X3Total} := P_{X3} \cdot 2 = 204 \cdot kW$ Power needed during spin-up and spin-down. Only two thrusters will be on at a time.

Hall Thrusters Calculations Continued



HERMeS TDU-1:

NASA HERMeS TDU-1 thruster $t_{spinUp\_TDU1} := 250hr$

$T_{TDU1} := 0.61N$ $P_{TDU1} := 12.5kW$ $I_{TDU1\_sp} := 3000s$ $m_{TDU1} := 100kg$

$mdot_{xenon} := \frac{T_{TDU1}}{I_{TDU1\_sp} \cdot g} = 20.734 \cdot \frac{mg}{s}$ $m_{xenon} := mdot_{xenon} \cdot t_{spinUp\_TDU1} = 18.661\,kg$

Total mass for Hall Thruster system:

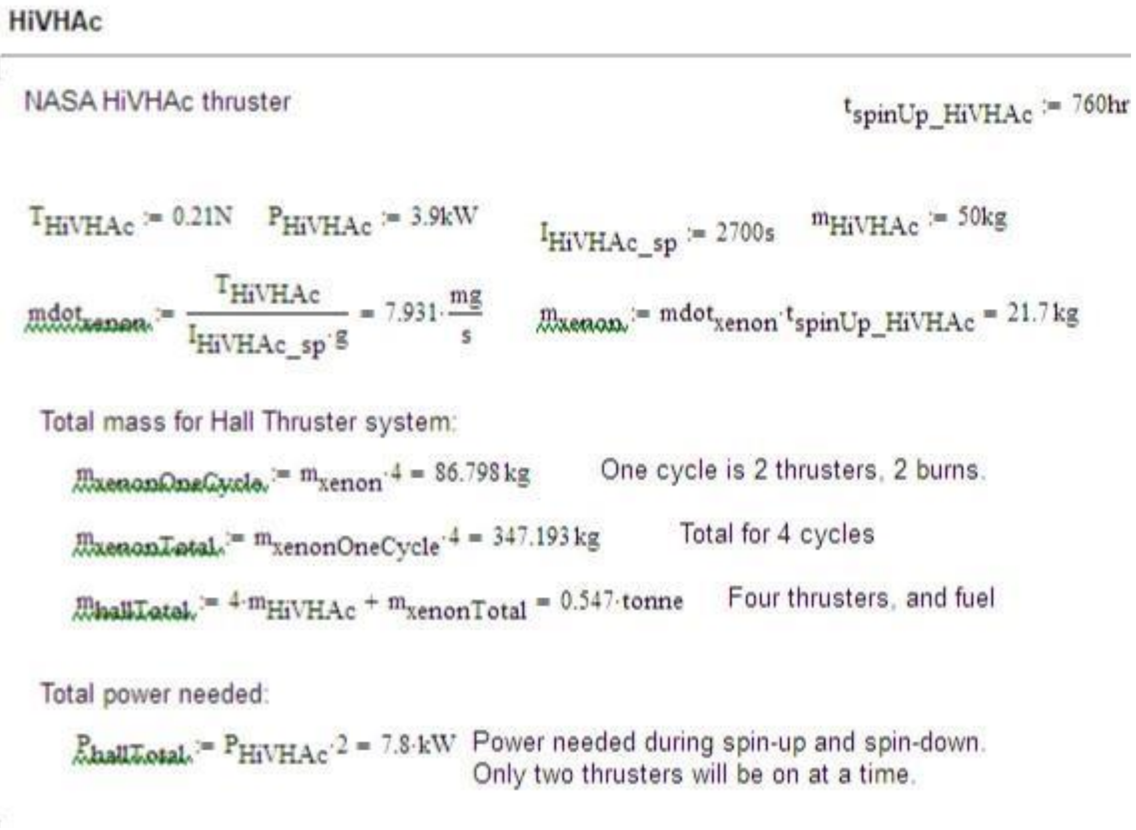
$m_{xenonOneCycle} := m_{xenon} \cdot 4 = 74.643\,kg$ One cycle is 2 thrusters, 2 burns.

$m_{xenonTotal} := m_{xenonOneCycle} \cdot 4 = 298.573\,kg$ Total for 4 cycles

$m_{hallTotal} := 4 \cdot m_{TDU1} + m_{xenonTotal} = 0.699 \cdot tonne$ Four thrusters, and fuel

Total power needed:

$P_{hallTotal} := P_{TDU1} \cdot 2 = 25 \cdot kW$ Power needed during spin-up and spin-down.
Only two thrusters will be on at a time.



HiVHAc

NASA HiVHAc thruster $t_{spinUp\_HiVHAc} := 760hr$

$T_{HiVHAc} := 0.21N$ $P_{HiVHAc} := 3.9kW$ $I_{HiVHAc\_sp} := 2700s$ $m_{HiVHAc} := 50kg$

$mdot_{xenon} := \frac{T_{HiVHAc}}{I_{HiVHAc\_sp} \cdot g} = 7.931 \cdot \frac{mg}{s}$ $m_{xenon} := mdot_{xenon} \cdot t_{spinUp\_HiVHAc} = 21.7\,kg$

Total mass for Hall Thruster system:

$m_{xenonOneCycle} := m_{xenon} \cdot 4 = 86.798\,kg$ One cycle is 2 thrusters, 2 burns.

$m_{xenonTotal} := m_{xenonOneCycle} \cdot 4 = 347.193\,kg$ Total for 4 cycles

$m_{hallTotal} := 4 \cdot m_{HiVHAc} + m_{xenonTotal} = 0.547 \cdot tonne$ Four thrusters, and fuel

Total power needed:

$P_{hallTotal} := P_{HiVHAc} \cdot 2 = 7.8 \cdot kW$ Power needed during spin-up and spin-down.
Only two thrusters will be on at a time.

Power Budget

Expansion/Contraction Usage:

Subsystem	Power Required (kW)
Expansion Motors	115
Peak Power - Habitat Pod	24
Peak Power - Storage Pod	24
Heated Water Line	2.54
Total	165.54

Rotation Usage:

Subsystem	Power Required (kW)
Torque Cancelling Motors	241
Peak Power - Habitat Pod	24
Peak Power - Storage Pod	24
Heated Water Line	2.54
Robotic Systems	3.6
Total	295.14

Solar Panel Degradation

Year	% Life Remaining	Power Available (kW)
1	100	750.00
2	98.5	738.75
3	97.02	727.67
4	95.57	716.75
5	94.13	706.00
6	92.72	695.41
7	91.33	684.98
8	89.96	674.71
9	88.61	664.59
10	87.28	654.62
11	85.97	644.80
12	84.68	635.13
13	83.41	625.60
14	82.16	616.21
15	80.93	606.97

As the solar panels begin to age, the power required and power available may become a problem. Based on a preliminary power budget for expansion/contraction and rotation, there will not be much power to spare after the electric thrust system takes what it needs.

Airlocks

NanoRacks

- Advantages:
  - Cutting edge technology
  - Safe for astronauts
  - Costs $12-15 million
- Disadvantages:
  - Larger than Japanese version

Quest Airlock

- Advantages:
  - Mature technology
  - Safe for astronauts
  - Little loss of environmental consumables
- Disadvantages:
  - Older technology
  - Costs $164 million
  - Much larger than NanoRacks

Robotic Track Trade Study

- Robotic Web
  - Already a part of Spidernaut's design and cost
  - Still under development by Purdue University
  - Complicated system
- Cable System and Motor
  - Downside of needing additional motors that use power
  - Simple system
- Truss System
  - Heavy
  - Complex
- Ladder System
  - Simple system
  - Downside is that halfway down gravity changes which poses a problem

- Chosen Design: Cable System and Motor

RASC-AL Concept Schedule

1. Launch partially outfitted with HPS (Transit Habitat)
2. Launch storage pod, robotic system, and central hub
3. Resupplied with a series of logistic flights prior to crew arrival
4. Transit system delivered to LDRO via propulsion kit or in-space transportation stage (6 months)
5. In ICH habitat mates with initial cis-lunar habitat to facilitate aggregation, crew checkout, and mission prep
6. Transit habitat undergoes 180 day checkout period to test systems, install other components, load supplies, and ensure habitat is ready
7. Systems will be in quiescent state so there is minimum prep the mission crew will need to perform before departure
8. Transit vehicle departs from ICH and moves to LDHEO to pick crew up (6 months)

RASC-AL Concept Schedule

9. Execute gravity assist to go to Mars
10. Transit to Mars (230-400 days)
11. Mars transit vehicle rendezvous with destination vehicle which is the crew descent vehicle to Mars
12. Crew departs to surface of Mars and habitat now works autonomously while in 5 sol orbit (300-550 days)
13. Mission completes and return to habitat
14. Return to Earth (200-360 days)
15. Crew transfers to Orion in LDHEO and returns to Earth
16. Transit system returns to LDRO and ICH so reset crew can refurbish it and prep for next mission

Possible Mission Schedule

1. Crew to Phobos
    - Departs Earth March 2, 2033
    - Arrives at Mars on January 1, 2034
    - Surface mission 417 days
    - Departs Mars on February 22, 2035
    - Arrives at Earth on January 4, 2036
    - Total heliocentric duration – 1,038 days
2. Crew to Mars
    - Departs Earth August 3, 2039
    - Arrives at Mars on September 6, 2040
    - Surface mission 300 days
    - Departs Mars on July 3, 2041
    - Arrives at Earth on June 28, 2042
    - Total heliocentric duration – 1,060 days

Possible Mission Schedule

3. Crew to Mars
    - Departs Earth October 23, 2043
    - Arrives at Mars on October 27, 2044
    - Surface mission 300 days
    - Departs Mars on August 23, 2045
    - Arrives at Earth on September 14, 2046
    - Total heliocentric duration – 1,057 days
4. Retirement or Retrofit

Relationships

- Mass Changes in the System
  - Center of gravity changes
  - Spin up/down time changes
  - Expansion/contraction time changes
  - Amount of thruster fuel needed changes
  - Amount of torque generated by pod system changes which could effect the torque cancelling motor
  - Loads change
    - Supports' dimensions change
    - Bracing changes
- Pipe Size
  - Flowrate changes which changes the additional rigidity added to expandable shaft

Risk and Mitigation

Risk	**Mitigation**
1. Mass Limit – 50 metric tons	1. Reduce redundancy in pods and use lighter materials
2. Thruster fuel consumption	2. Limit the number of times thrusters are used and reduce mass in other areas to allow for more thruster fuel on board
3. Pod system hits solar panels	3. Extend the central hub to a distance that is past the range of the solar panels

Risks and Mitigation

Risk	**Mitigation**
4. Electric power consumption exceeds solar panel output	4. Reduce the number of systems that need to run simultaneously
5. Power consumption during spin up is too high to be able to run life support	5. Astronauts may need to wear spacesuits during spin up/down Use anti-torque motor to prevent rotation
6. Propulsion system rotates	6. Use anti-torque motor to prevent rotation
7. Piping fails	7. Provide redundant water and waste bags

Risks and Mitigation

Risks	**Mitigation Plan**
8. Asteroid Impact	8. Robot to patch holes
9. Robotic Systems Fail	9. Shaft is large enough for a person in a spacesuit and have redundant supplies in each pod
10. Bearings Lock Up	10. Spare bearings
11. Thruster Failure	11. Spare thruster if possible or use torque motor to help rotate
12. Separation of Pods from Propulsion System	12. Create the system with sufficient factors of safety

Risks and Mitigation

Risks	Mitigation Plan
13. Waste Pipe Clogs	13. Cleaning system in pipe to clear pipe
14. Expandable Shaft Environmental Controls Failure	14. Redundant water stored on habitat side
15. Extreme Temperature Stresses the System	15. Choose materials that can withstand extreme temperatures
16. Boom Fatigue	16. Redundant reels if possible
17. Connection Failure	17. Redundant connections that can take the additional loads