Gravity Simulation Platform On-Orbit: A Testbed

Master's Project: Space Architecture, Fall 2019

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M.S. in Space Architecture Student, SICSA, Dept. of Mechanical Engineering, University of Houston.

Committee members: Prof. Larry Bell Prof. Olga Bannova Prof. Larry Toups Prof. Kriss Kennedy

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Prof. Larry Bell
Prof. Olga Bannova
Mr. Larry Toups
Mr. Kriss Kennedy

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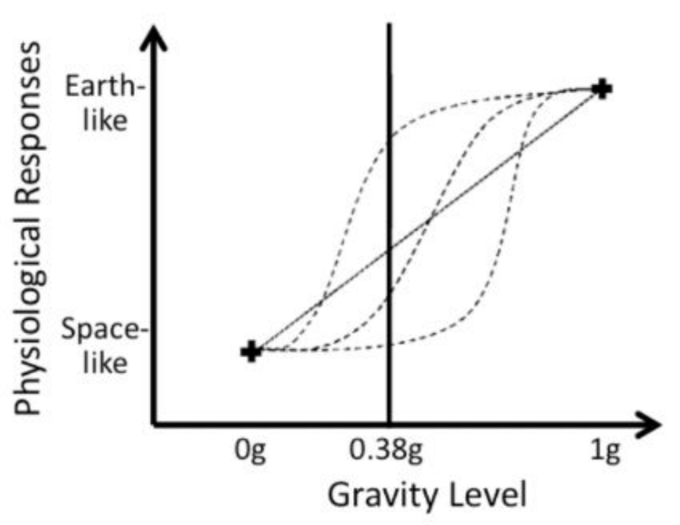
Timothy Bishop
Justin Lin
Les Johnson
Justin Rowe
Amandarose Kiger

Safety

Long Term Human Presence
In LEO, Mars & Beyond

Vision

Issue: Knowledge Gap In Long Term Effects Of Partial Gravity



Source: Artificial Gravity Evidence Report, Human Research Program, Human Health Countermeasures Element, Version 6, May 2015, Gilles Clément

"The effects of Martian gravity on

the human sensorimotor, cardiovascular, musculoskeletal, and immune systems, as well as effects on behavior, general health and performance,

are unknown."

Source: International roadmap for artificial gravity research, November 2017, Gilles Clément

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NASA TA 7.4.4

NASA HRP

Human Health Countermeasures

Variable Gravity Research Platform In LEO

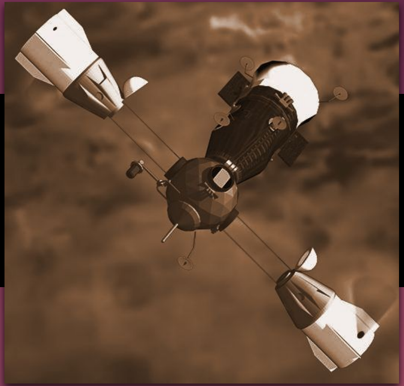
The Proposal

Credit: MIT

1

Phased Approach

Credit: MIT



1

2

Phased Approach

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Credit: MIT

1

2

Phased Approach

Credit: MIT

1

2

3

Phased Approach

Credit: MIT

1

2

3

Phased Approach

Phased Approach

1

Credit: MIT

2

3

4

Variable Gravity Research Platform

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Testbed

For Variable Gravity Research Platform In LEO

Thesis Proposal

Scope of Project

Conops
Constituent Elements Of Testbed
Test Objectives

Time, Forces, Technical Systems

Modifications - Constituent Elements Of The Testbed

Rudimentary Design Of The Tether System

In scope

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Design Of Subsystems

Test Activities Details

Interior Design Of The Testbed

Out of scope

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Project Statement

Low Cost Enabling Mission - Off The Shelf Products

Short Term Human Adaptations To Rotating Platforms

Low Cost Enabling Mission - Off The Shelf Products

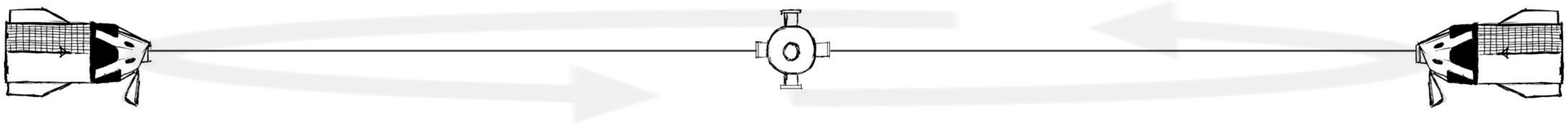
Short Term Human Adaptations To Rotating Platforms

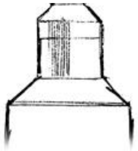
Preliminary Design Concept

3 Body System

2 Space Vehicles Tethered To Pressurized Central Hub

The Central Hub Docks To ISS Intermittently





Test Objectives

Technical

Physiological

2

3

Test subsystems

- ECLSS
- Thermal control
- GNC
- Power supply & distribution
- Propulsion & AAC

Test docking and transfer systems & protocols

Test spin-up and spin down systems & protocols

Test structural stability and integrity.

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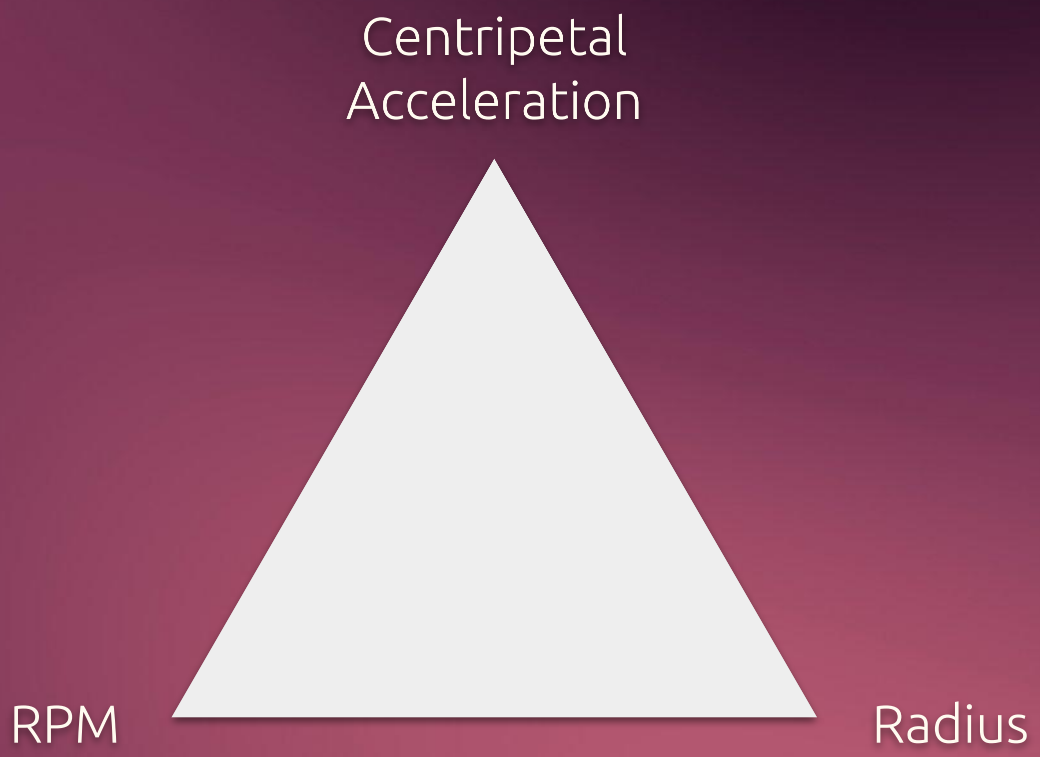
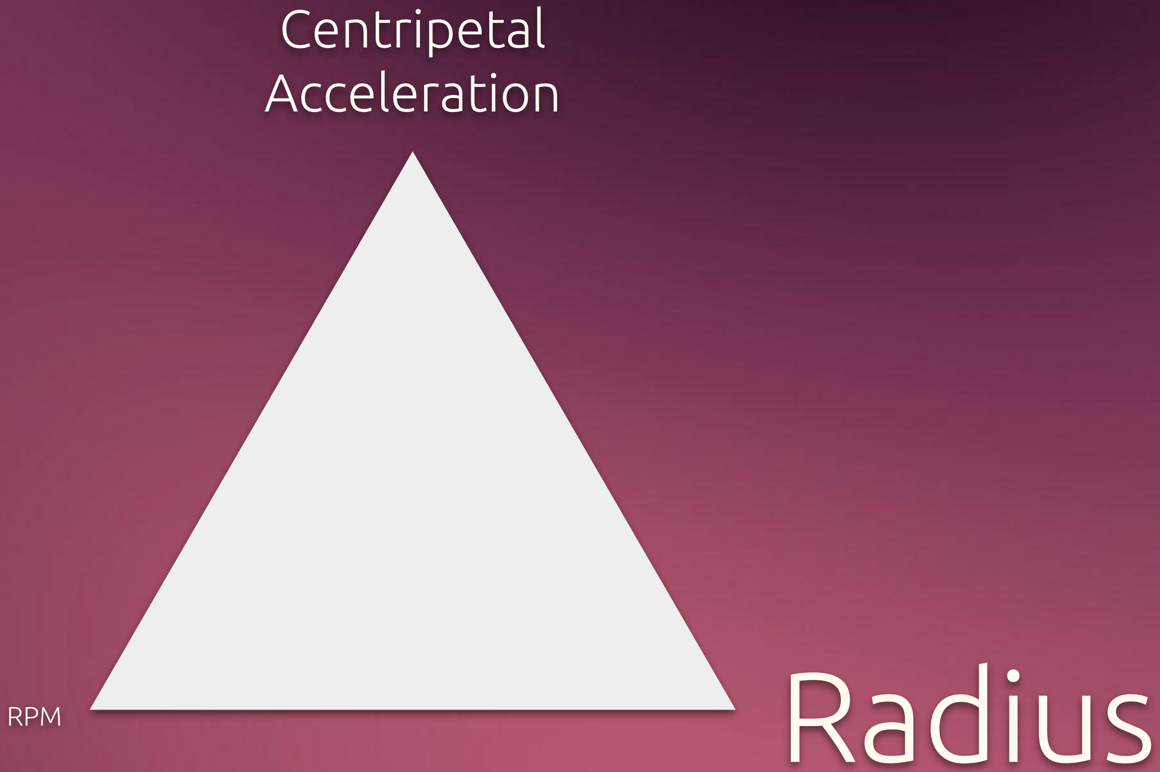
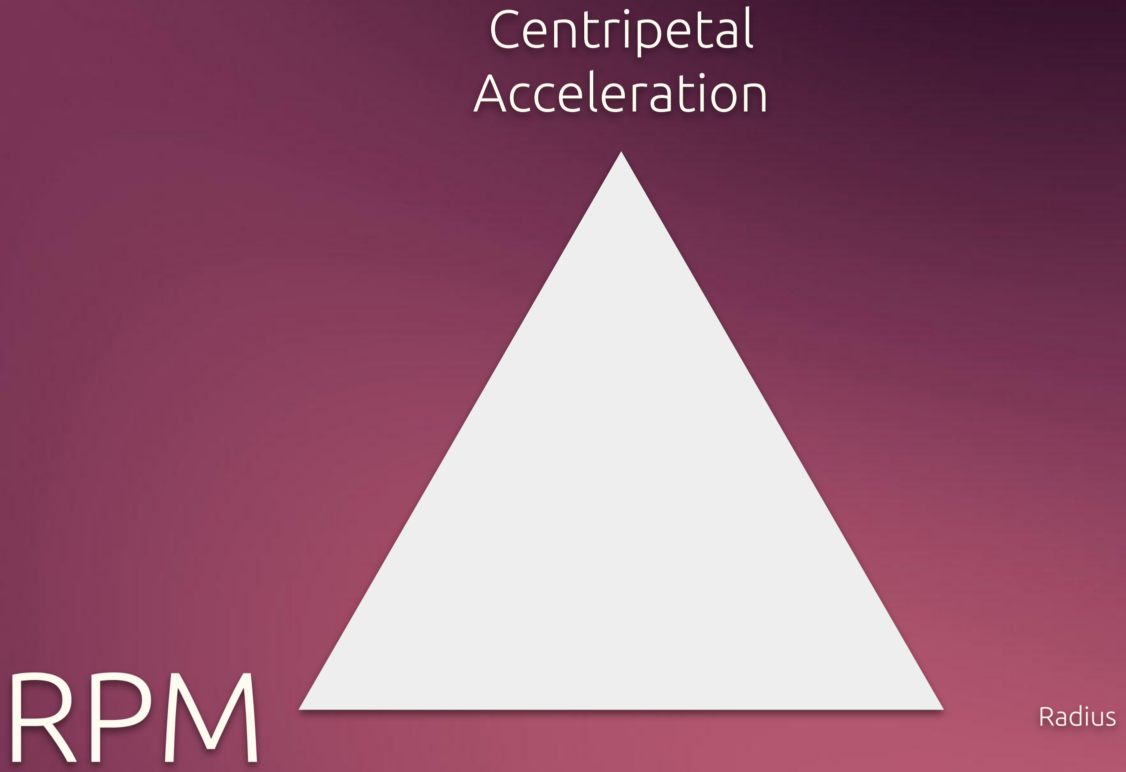
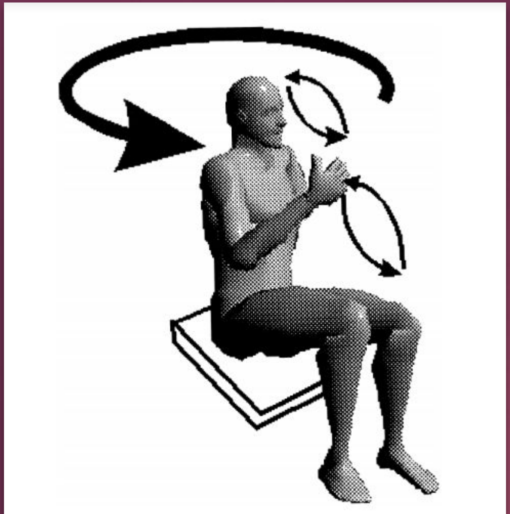

Centripetal Acceleration
RPM
Radius


Centripetal Acceleration
RPM
Radius


Centripetal Acceleration
RPM
Radius

Source: Adaptation in a rotating artificial gravity environment, James R. Lackner, Paul DiZio, 1998

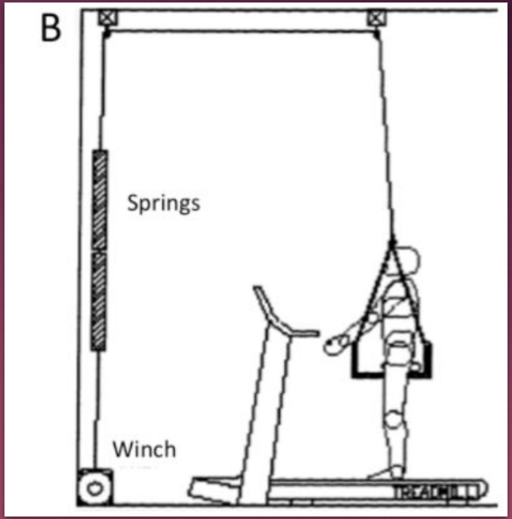


Test Response To Coriolis And Related Effects.

Test Response To Different Levels Of Gravity.

Test Response To Different Rates Of Angular Velocity And Radii.

Source: Artificial Gravity Evidence Report, Human Research Program, Human Health Countermeasures Element, Version 6, Gilles Clément, 2015



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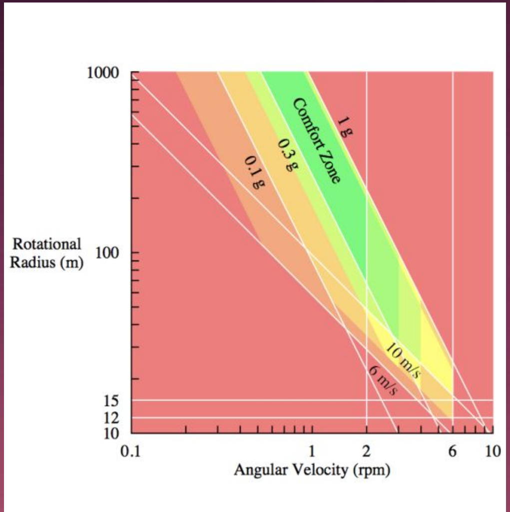
Source: Space Settlement Population Rotation Tolerance, Al Globus, Theodore Hall, 2017



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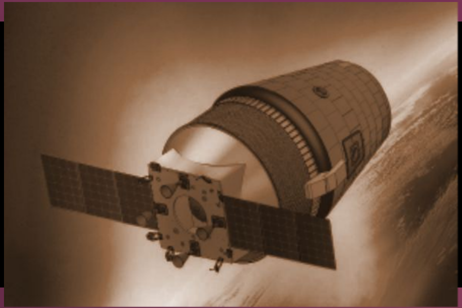
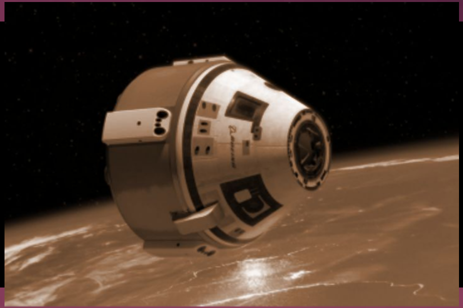
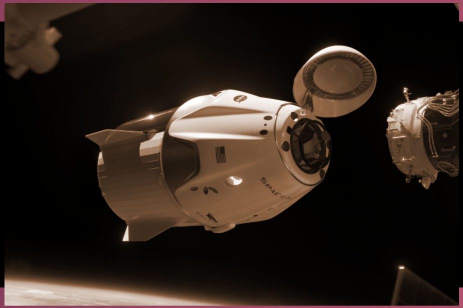
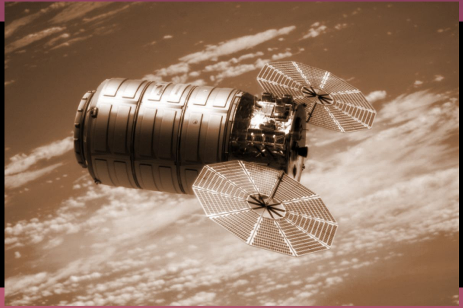
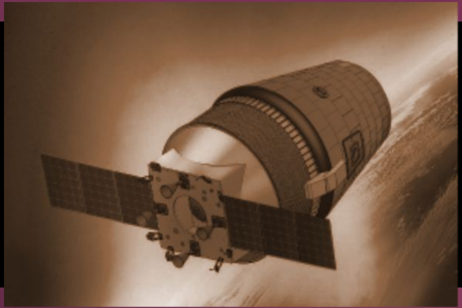
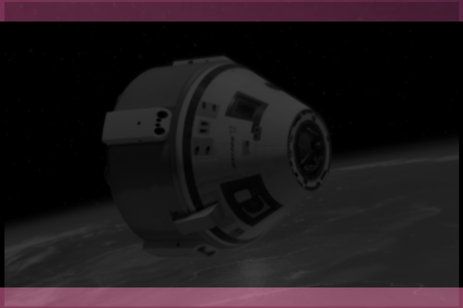
Space Vehicle Selection

Sidewall Angle, Habitable Volume, Cost, Operational Status



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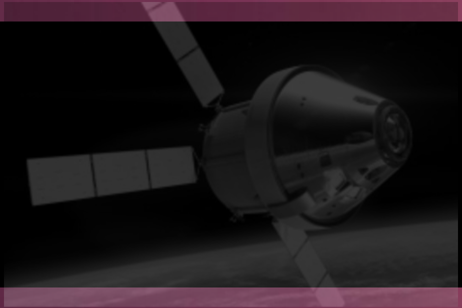
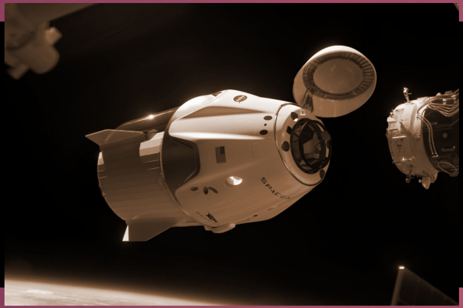


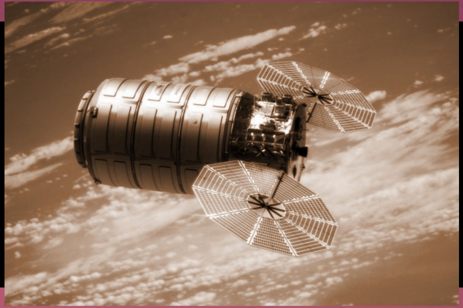

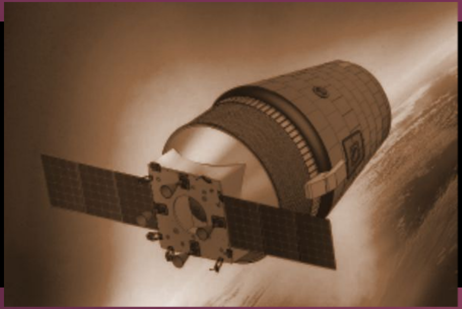

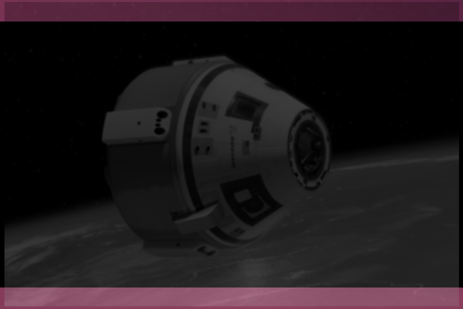

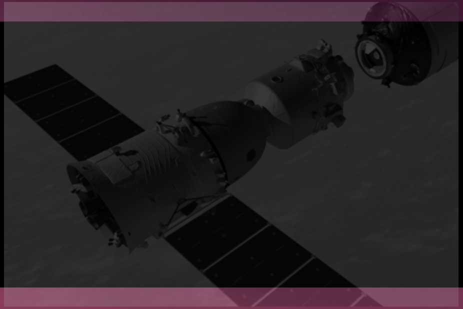

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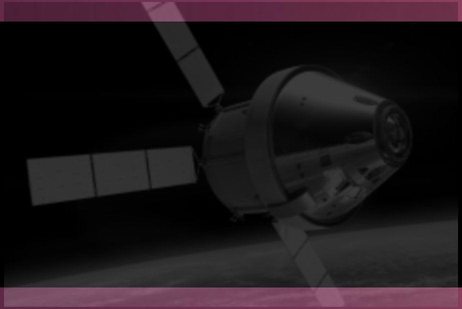

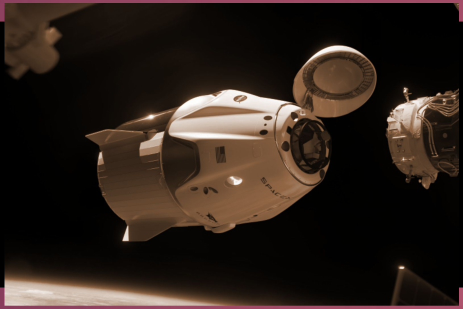

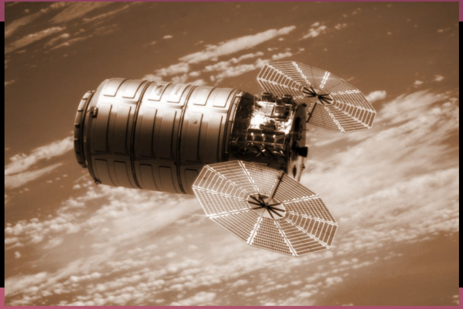

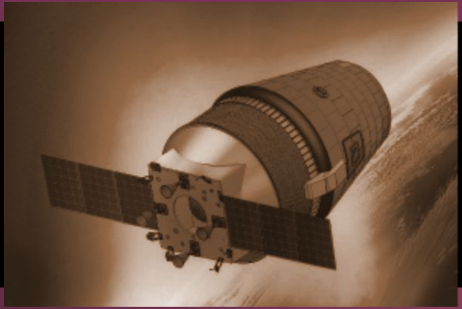
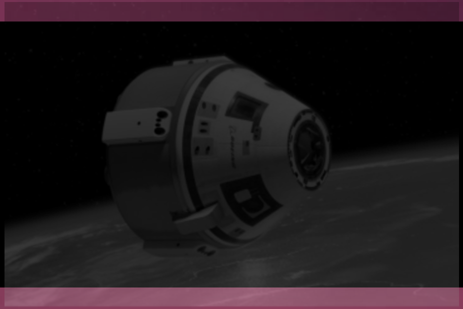
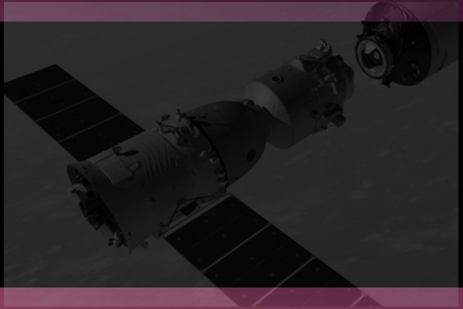


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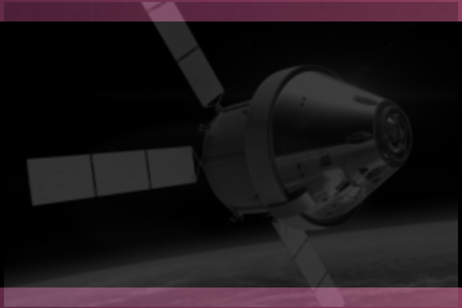
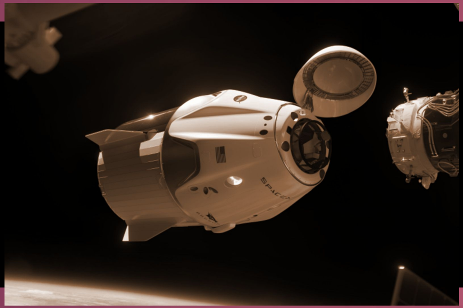

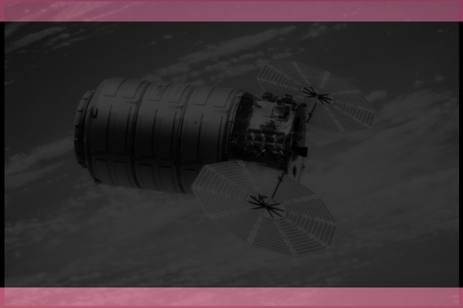

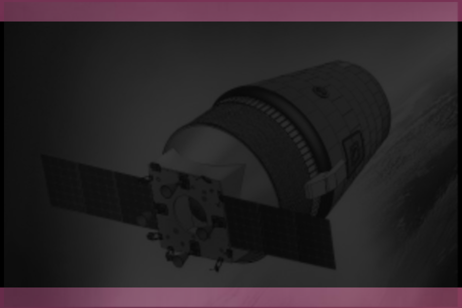
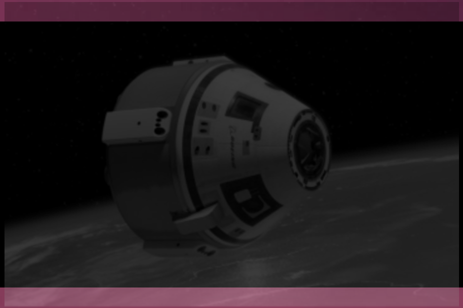
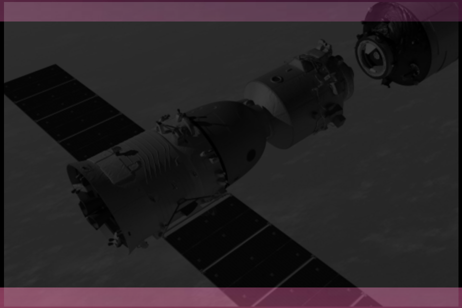
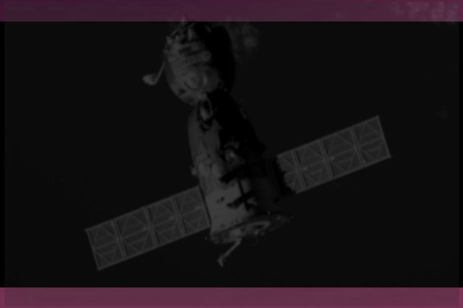

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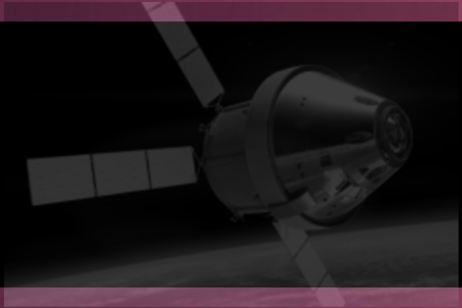
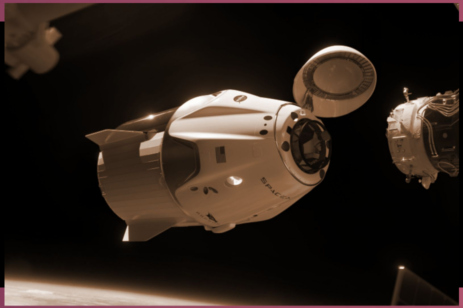
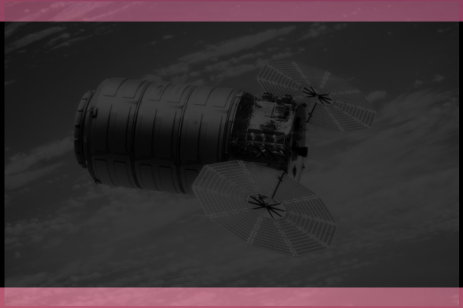
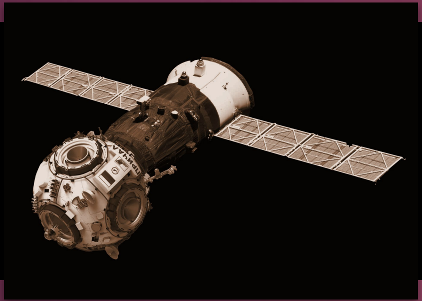
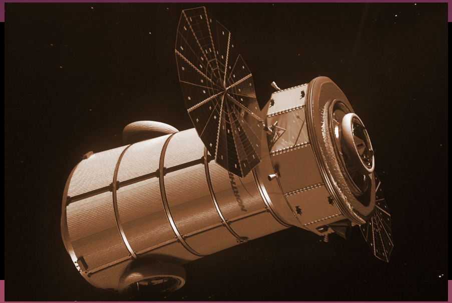



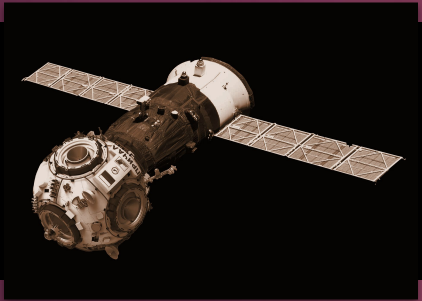


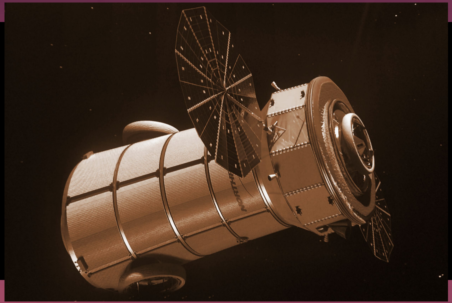
Central Hub Selection





Cost, Propulsion, Docking Ports, Operational Status





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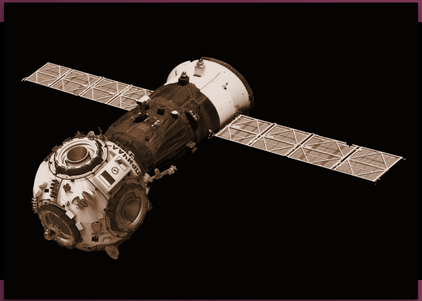

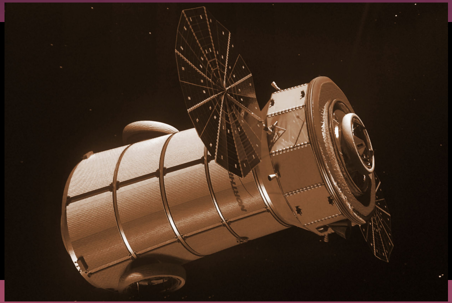

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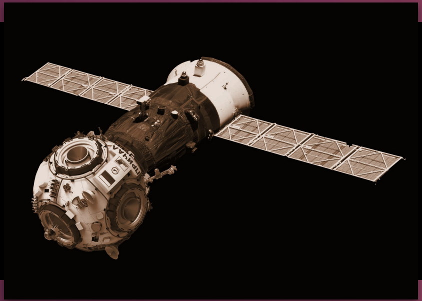


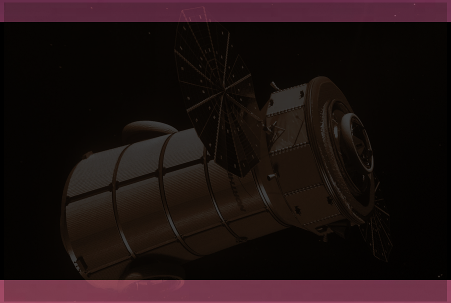

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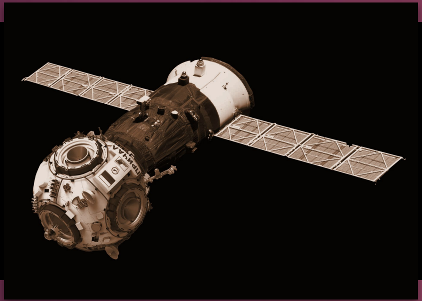
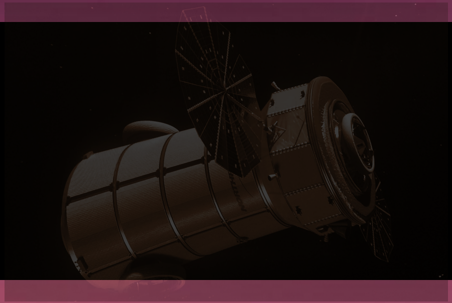
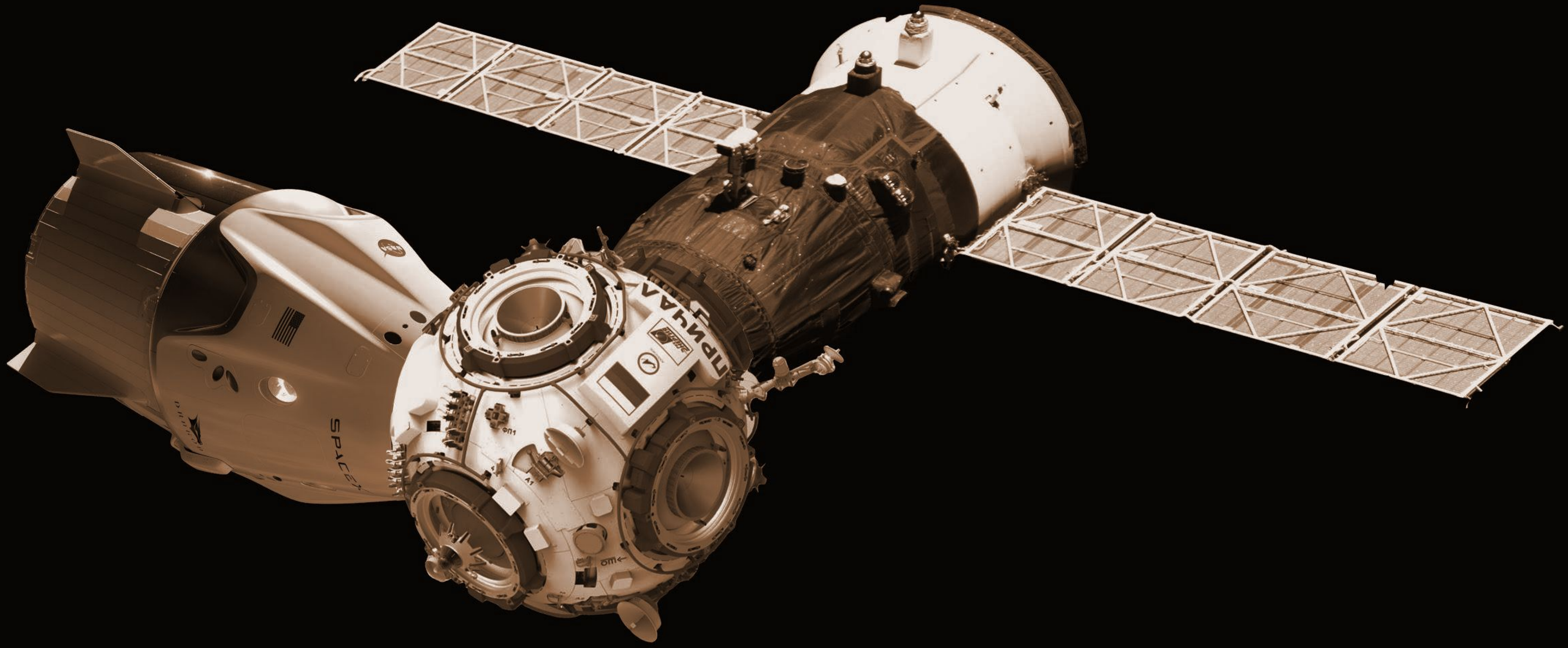


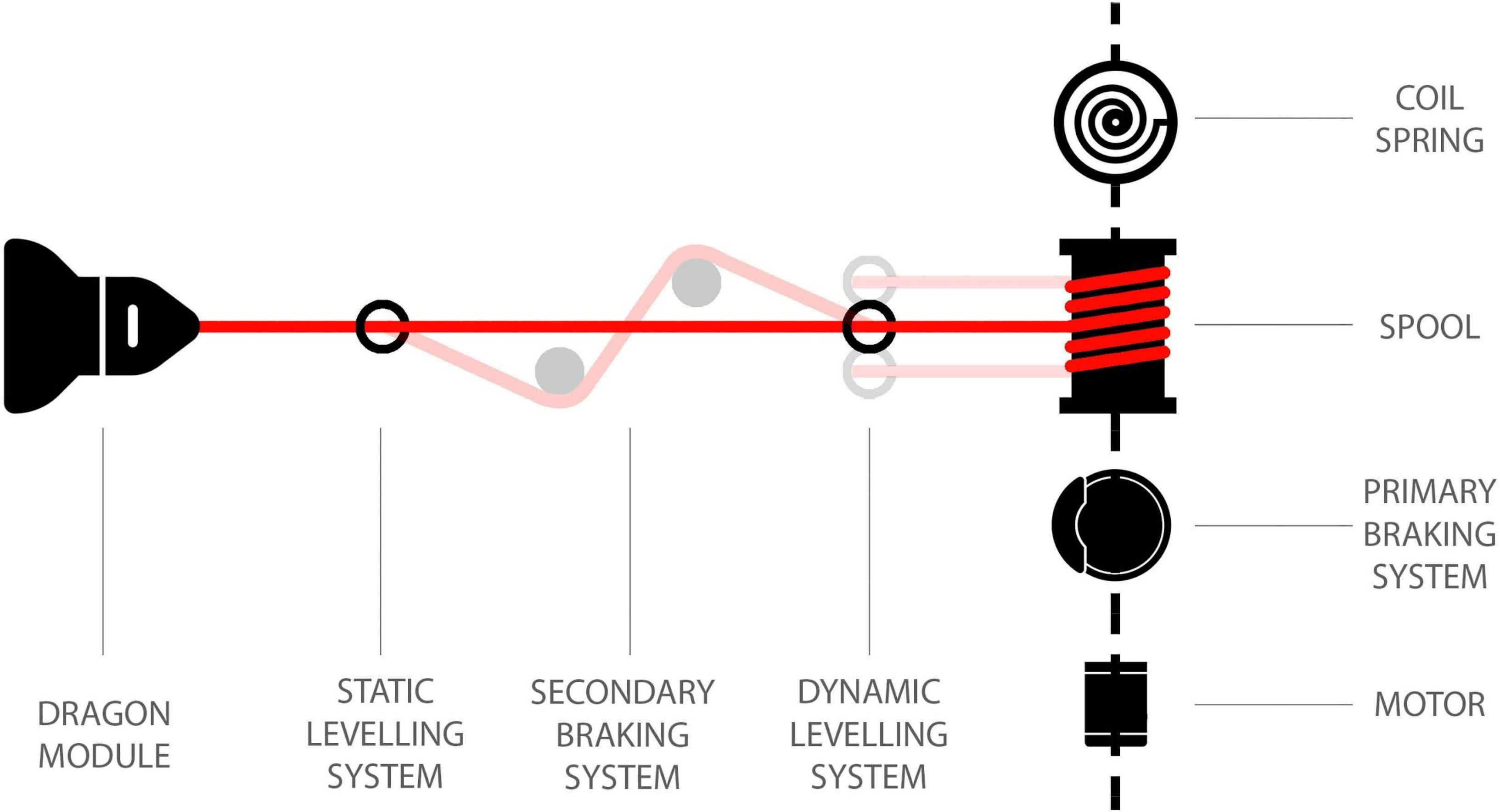


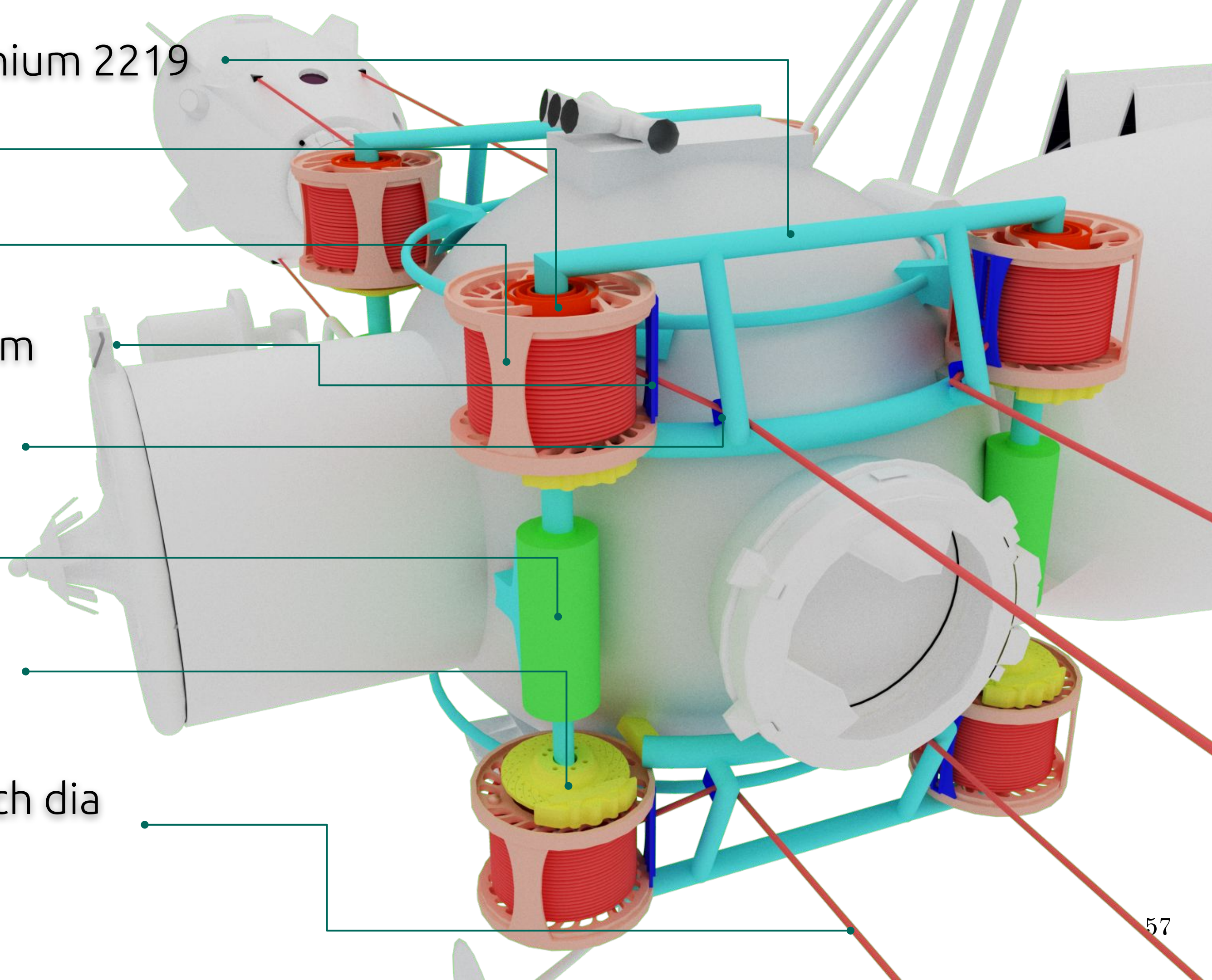
Prichal + Progress

Cost, Propulsion, Docking Ports, Operational Status



Customization of Central Hub


COIL SPRING
SPOOL
PRIMARY BRAKING SYSTEM
MOTOR
DRAGON MODULE
STATIC LEVELLING SYSTEM
SECONDARY BRAKING SYSTEM
DYNAMIC LEVELLING SYSTEM

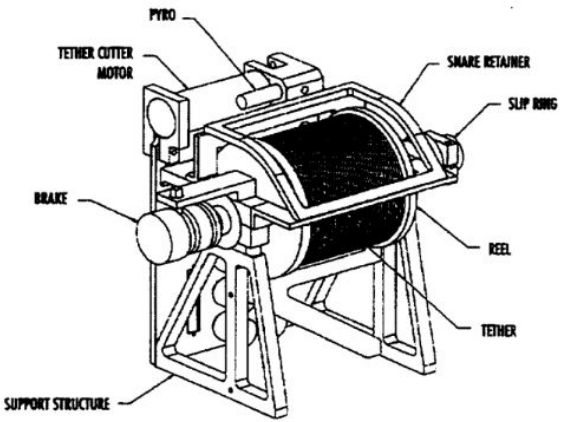

Frame Assembly, Aluminium 2219
Coil Spring
Spool
Dynamic Levelling System
Static Levelling System
Motor
Primary Braking System
Toro^{tm} 12 Strand 1-⅛ inch dia
100 m

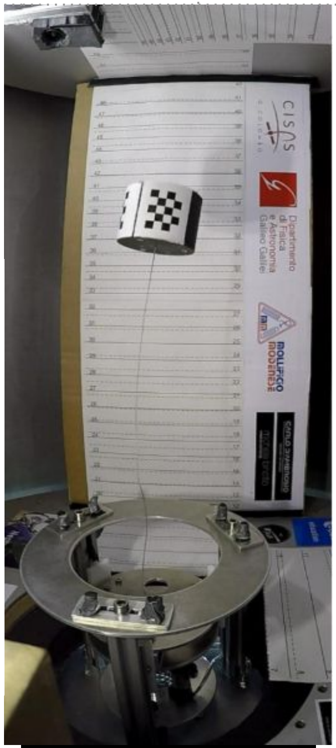
Toro™ 12 Strand

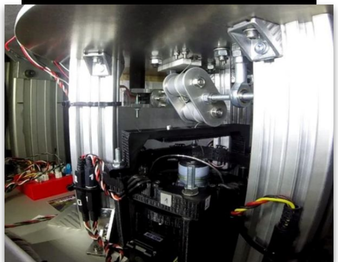
1-⅛” Diameter
10 Factor Of Safety
100” max. Tether Length

The Oedipus-C Tether deployer

Credits: CSA & NASA





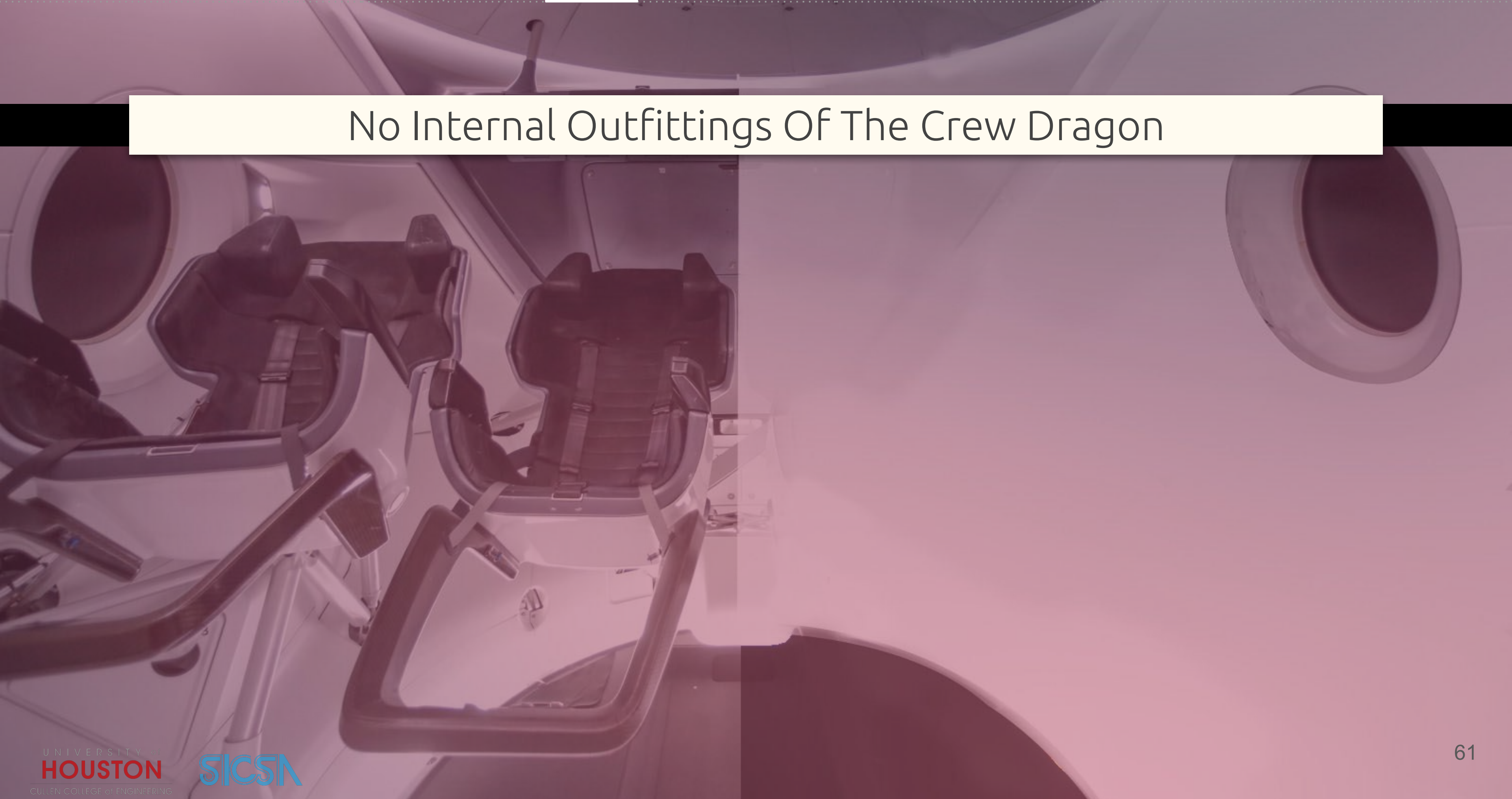


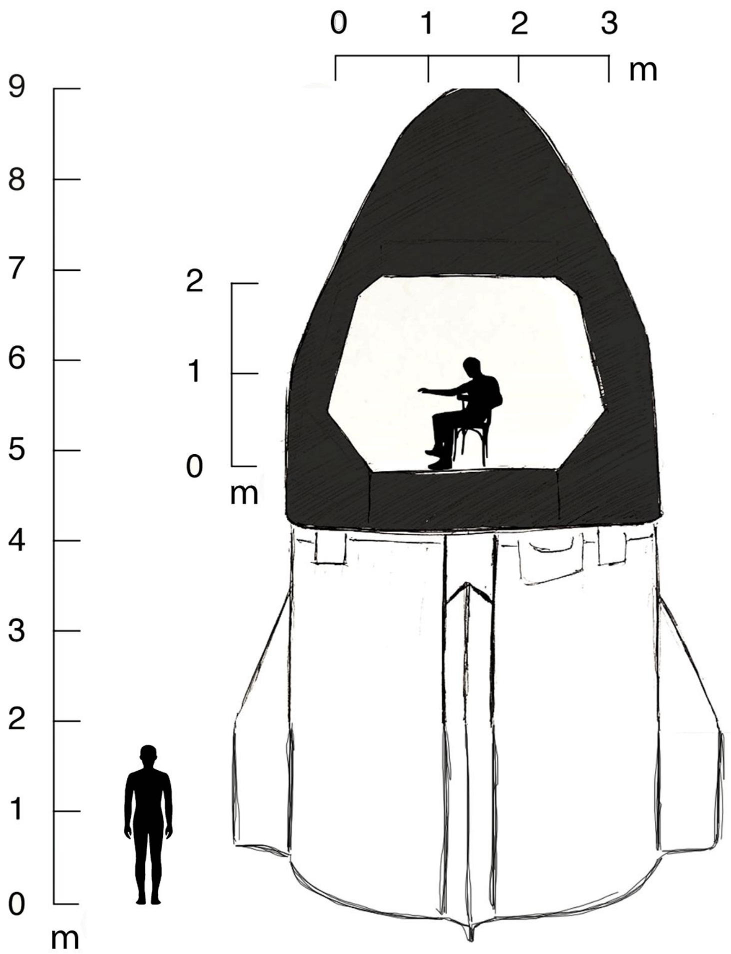
Space Tether Automatic Retrieval (STAR)

Credits: DLR & ESA

Customization of Dragon Modules

No Internal Outfittings Of The Crew Dragon




0
1
2
3
m
9
8
7
6
5
4
3
2
1
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m
2
1
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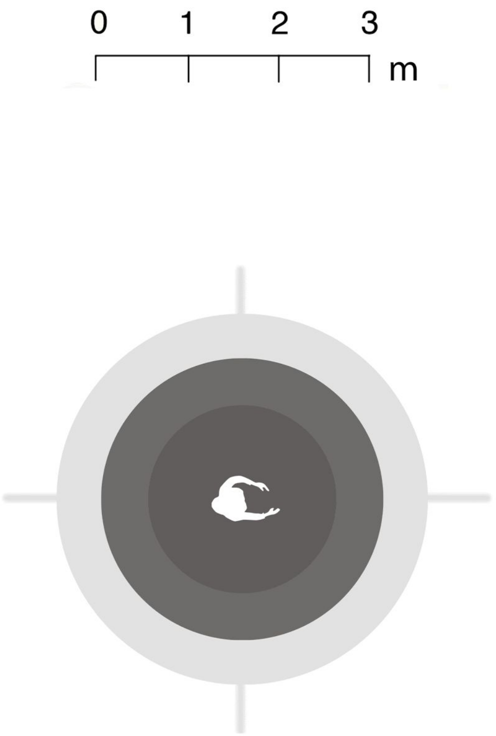
m


0
1
2
3
m

No Superdraco Thrusters

Spin-up Thrusters Introduced In The Service Module

Hooks For Tether System Introduced

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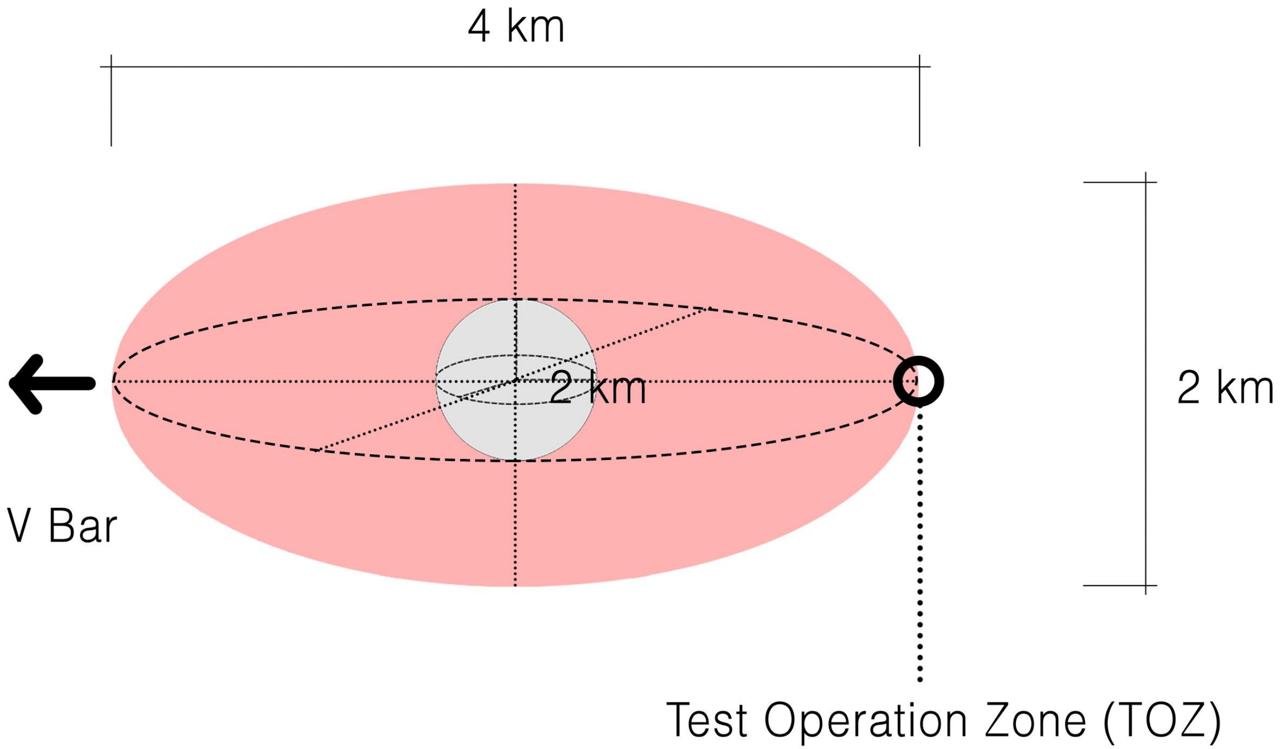
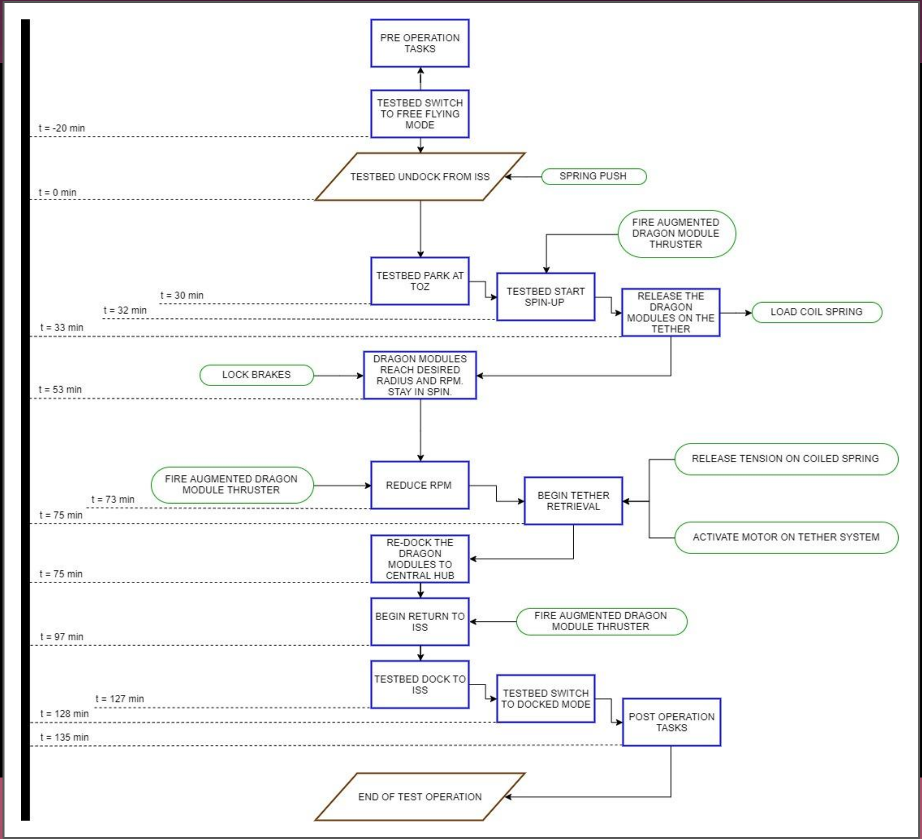
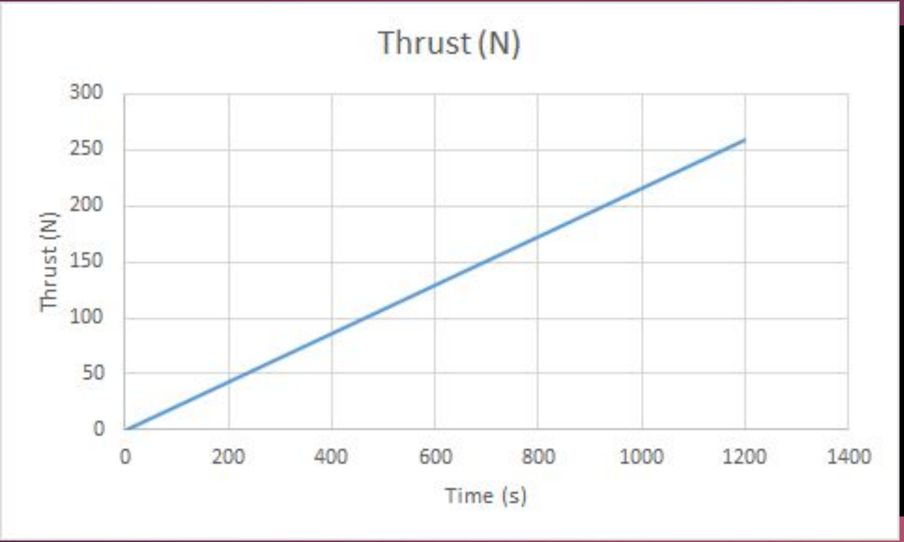
ConOps

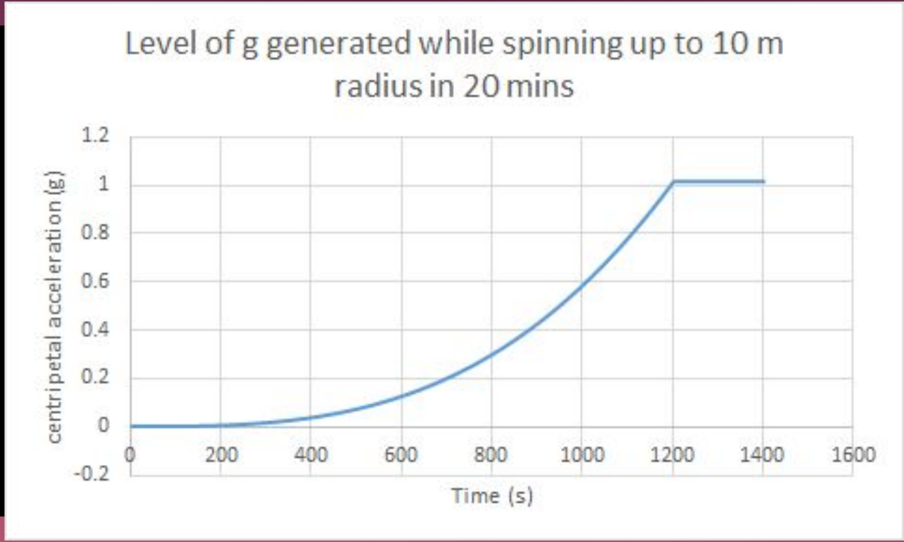
Testbed System	Docked mode	Free flying mode
Solar Arrays	Extended	Retracted
Electrical power supply	Charging batteries	On
ECLSS	Off	On
Comms	Off	On
GNC	Off	On


4 km
2 km
2 km
V Bar
Test Operation Zone (TOZ)

TEST NAME	T1
SPIN RADIUS	10 M
RPM	9.5
G	1
SPIN DURATION	20 MINS

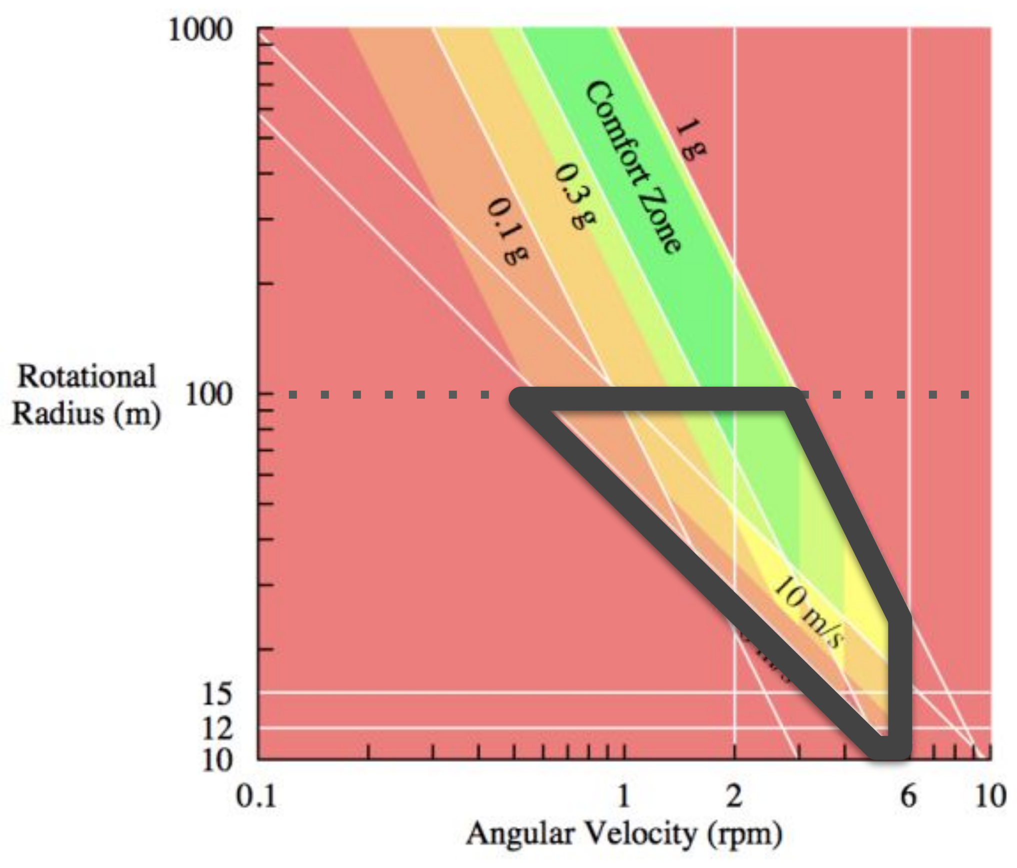

PRE OPERATION TASKS
TESTBED SWITCH TO FREE FLYING MODE
t = -20 min
TESTBED UNDOCK FROM ISS
SPRING PUSH
t = 0 min
FIRE AUGMENTED DRAGON MODULE THRUSTER
TESTBED PARK AT TOZ
TESTBED START SPIN-UP
RELEASE THE DRAGON MODULES ON THE TETHER
LOAD COIL SPRING
t = 30 min
t = 32 min
t = 33 min
LOCK BRAKES
DRAGON MODULES REACH DESIRED RADIUS AND RPM. STAY IN SPIN.
t = 53 min
RELEASE TENSION ON COILED SPRING
FIRE AUGMENTED DRAGON MODULE THRUSTER
REDUCE RPM
BEGIN TETHER RETRIEVAL
t = 73 min
t = 75 min
ACTIVATE MOTOR ON TETHER SYSTEM
RE-DOCK THE DRAGON MODULES TO CENTRAL HUB
t = 75 min
BEGIN RETURN TO ISS
FIRE AUGMENTED DRAGON MODULE THRUSTER
t = 97 min
TESTBED DOCK TO ISS
TESTBED SWITCH TO DOCKED MODE
POST OPERATION TASKS
t = 127 min
t = 128 min
t = 135 min
END OF TEST OPERATION


Thrust (N)
Thrust (N)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
Time (s)


Level of g generated while spinning up to 10 m radius in 20 mins
centripetal acceleration (g)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
200
400
600
800
1000
1200
1400
1600
Time (s)

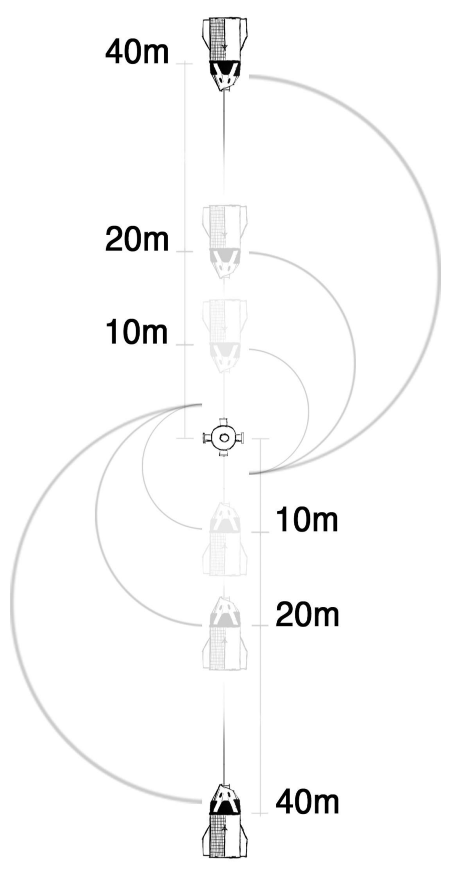
TEST NAME	Tn
SPIN RADIUS	100 M
RPM	3
G	1
SPIN DURATION	TBD

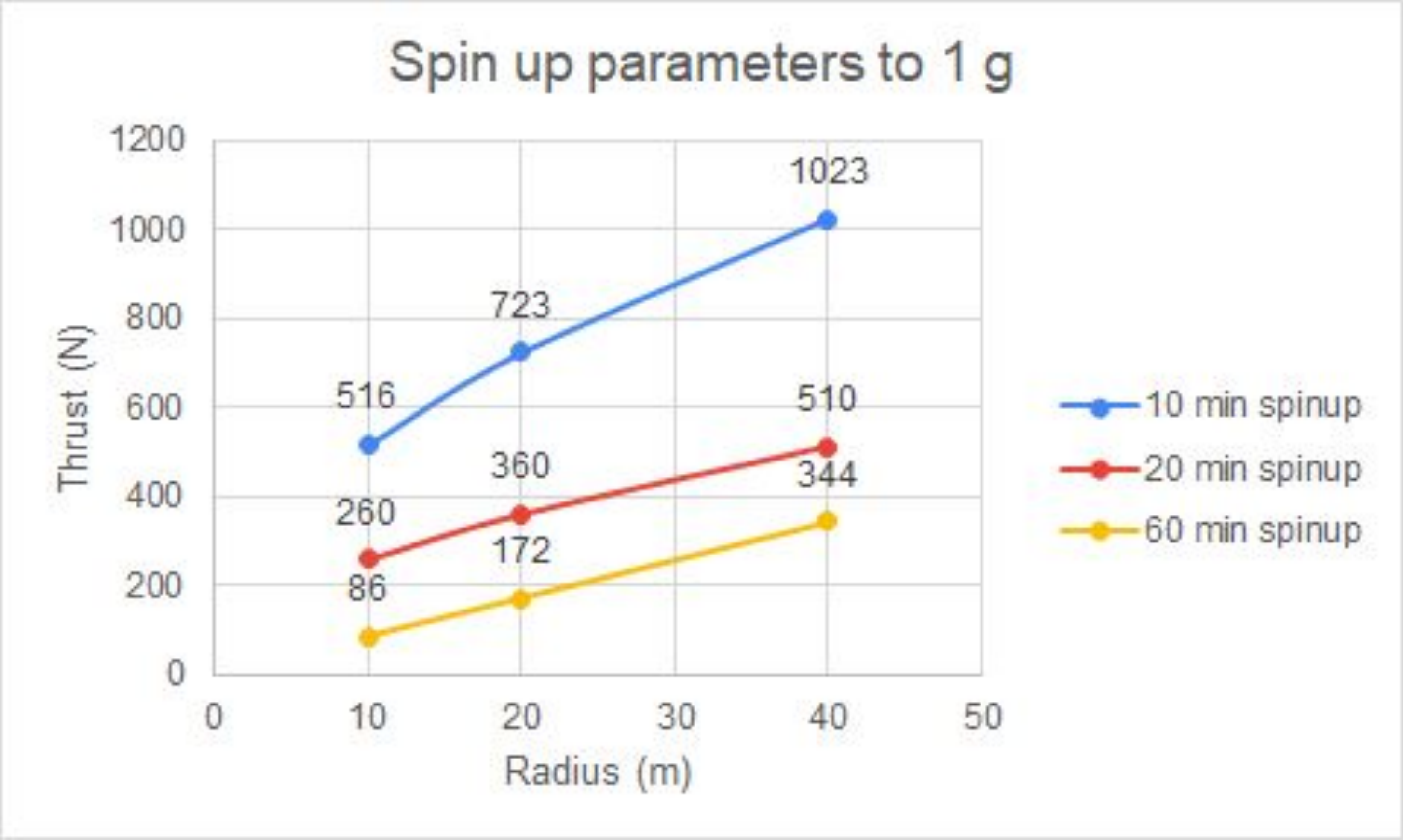
Adapted from: Space Settlement Population Rotation Tolerance, Al Globus, Theodore Hall, 2017



31 M-tons

Estimated Wet Mass Of Testbed


40m
20m
10m
10m
20m
40m


Spin up parameters to 1 g
Thrust (N)
Radius (m)
1200
1000
800
600
400
200
0
0
10
20
30
40
50
516
723
1023
260
360
510
86
172
344
10 min spinup
20 min spinup
60 min spinup

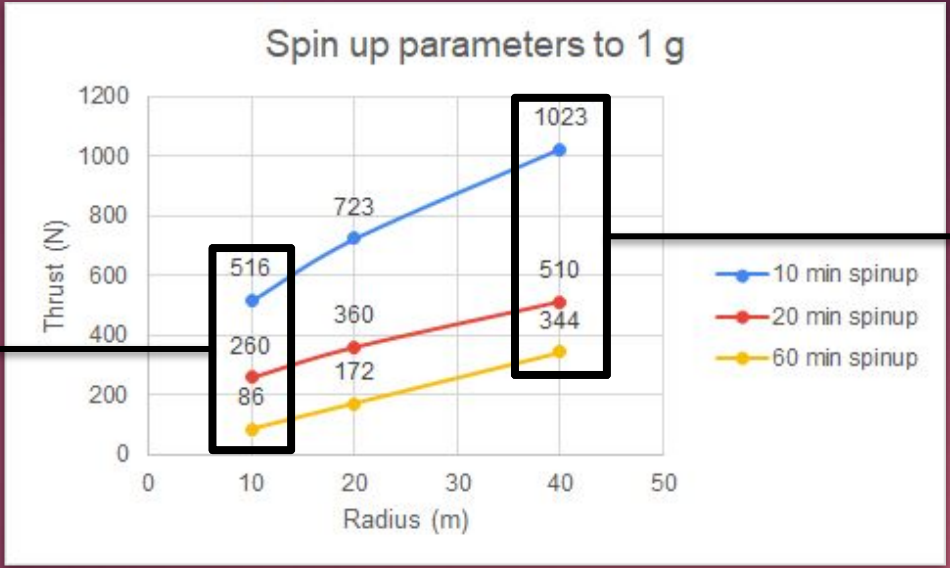
KDTU-80 Thruster Of Progress And Same Sized Fuel Tank

100 Kg

Of Fuel Spent Per Spin-up And Spin-down Cycle.

9

Cycles Before Refueling



200 Kg

Of Fuel Spent Per Spin-up And Spin-down Cycle.

5

Cycles Before Refueling

Assumptions

In-orbit Refueling Capability

Power - Free Flying Mode - Longest Test Operation

Costs Of Prichal, Progress Module, Developmental And Sustenance

In-orbit Refueling Capability

Power - Free flying Mode - Longest Test Operation

Costs Of Prichal, Progress Module, Developmental And Sustenance

In-orbit Refueling Capability

Power - Free Flying Mode - Longest Test Operation

Costs Of Prichal, Progress Module, Developmental And Sustenance

Risks & Mitigations

Static Discharge	→ Conductive Tether
Center of Gravity Offset	→ Variation In Tether Length
Hypergolic Fuels	→ Safer Fuel Mixtures / Thrusters.
Zvezda Docking Port Utilization	→ Alternate & Dedicated Docking Spot

Risk		Mitigation
Static Discharge	→	Conductive tether
Center of Gravity Offset	→	Variation In Tether Length
Hypergolic Fuels	→	Safer Fuel Mixtures / Thrusters.
Zvezda Docking Port Utilization	→	Alternate & Dedicated Docking Spot

Risk		Mitigation
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Risk		Mitigation
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Center of Gravity Offset	→	Variation In Tether Length
Hypergolic Fuels	→	Safer Fuel Mixtures / Thrusters.
Zvezda Docking Port Utilization	→	Alternate & Dedicated Docking Spot

Opportunities

Future Researchers Follow Up

Inform Design Standard Handbook For AG Habitat Interiors

Artificial Intelligence: Data Gathering

Use Beam As Precursor- Docking / Undocking Protocols

Adapt As Deep Space Transit

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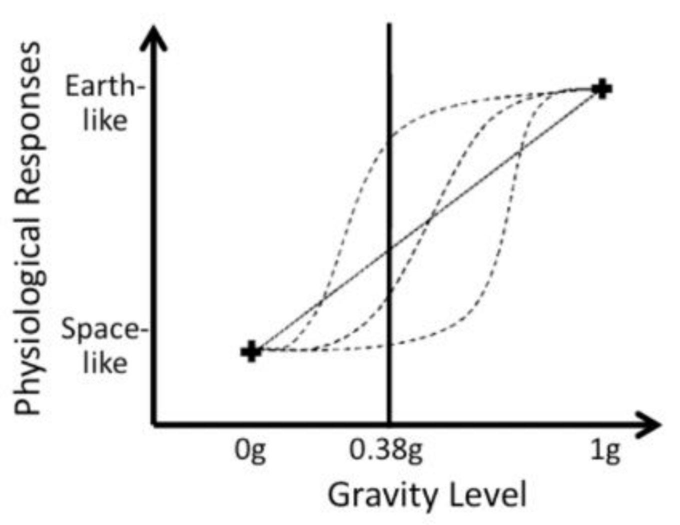
Adapt As Deep Space Transit

Path Forward

Smallsat testbed[2]

Conclusion

Issue: Knowledge Gap In Long Term Effects Of Partial Gravity

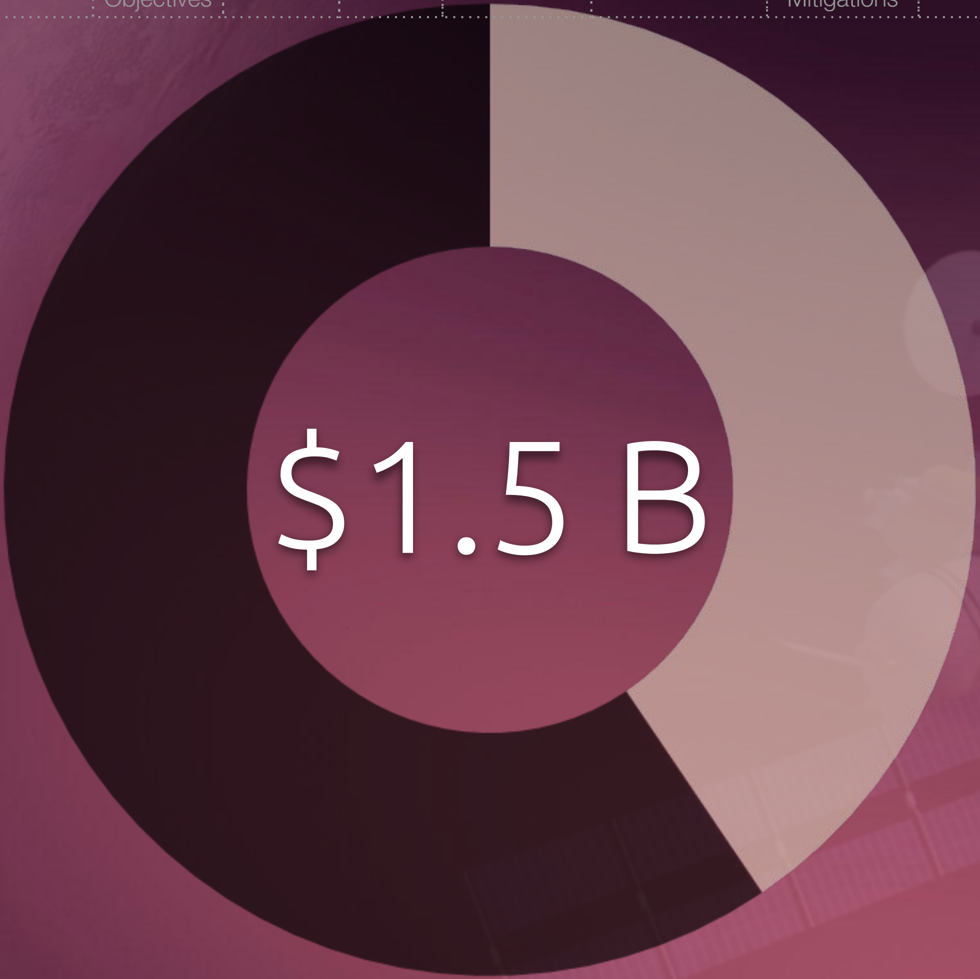


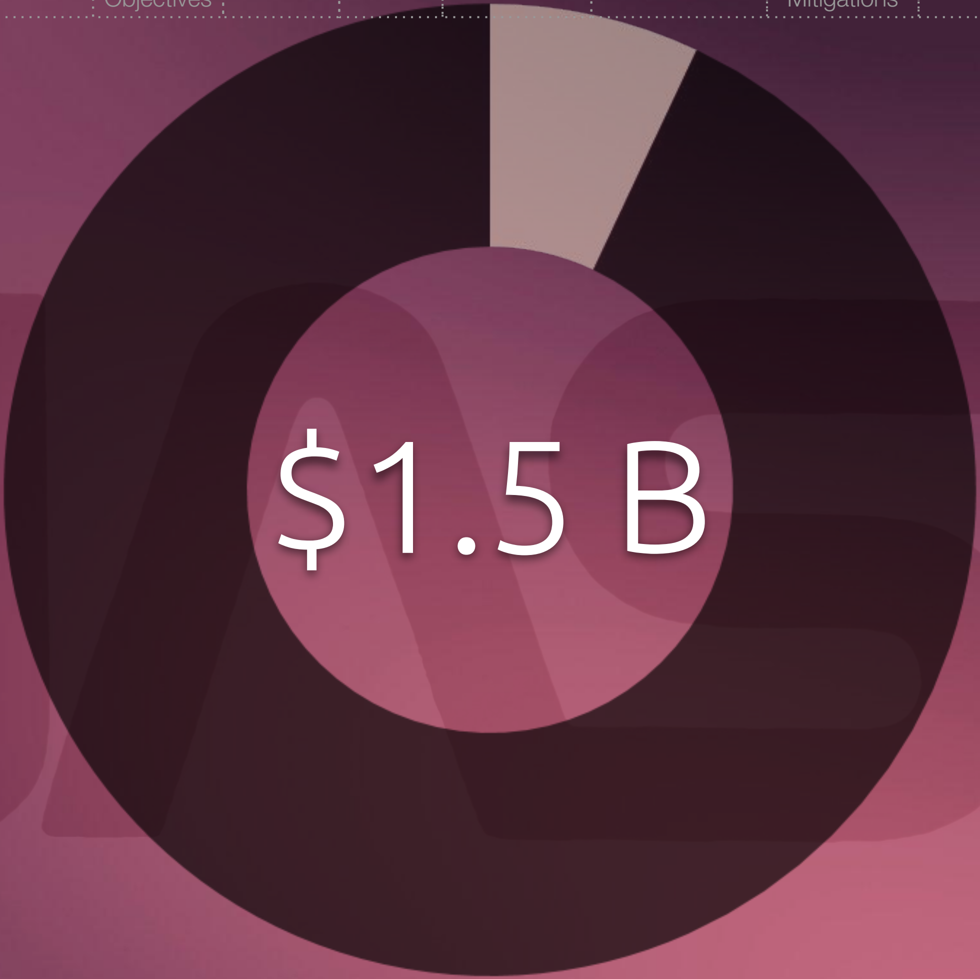
Source: Artificial Gravity Evidence Report, Human Research Program, Human Health Countermeasures Element, Version 6, May 2015, Gilles Clément

$1.5 B

Estimated Cost : Hardware + Launch + Development + Sustenance


$1.5 B


$1.5 B


$1.5 B

What bridges need to be built from current state to future state?

Image credits: NASA and SpaceX

Gravity Simulation Platform On-Orbit: A Testbed

Master's Project: Space Architecture, Fall 2019

Albert Rajkumar
M.S. in Space Architecture Student, SICSA, Dept. of Mechanical Engineering, University of Houston.

Committee members: Prof. Larry Bell Prof. Olga Bannova Prof. Larry Toups Prof. Kriss Kennedy

UNIVERSITY of HOUSTON
CULLEN COLLEGE of ENGINEERING
SICSA

TETHER

Dynamic Radii

Launch Friendly

TRUSS

Less Complex Operation

Stability

Telescopic / In-orbit Manufacture

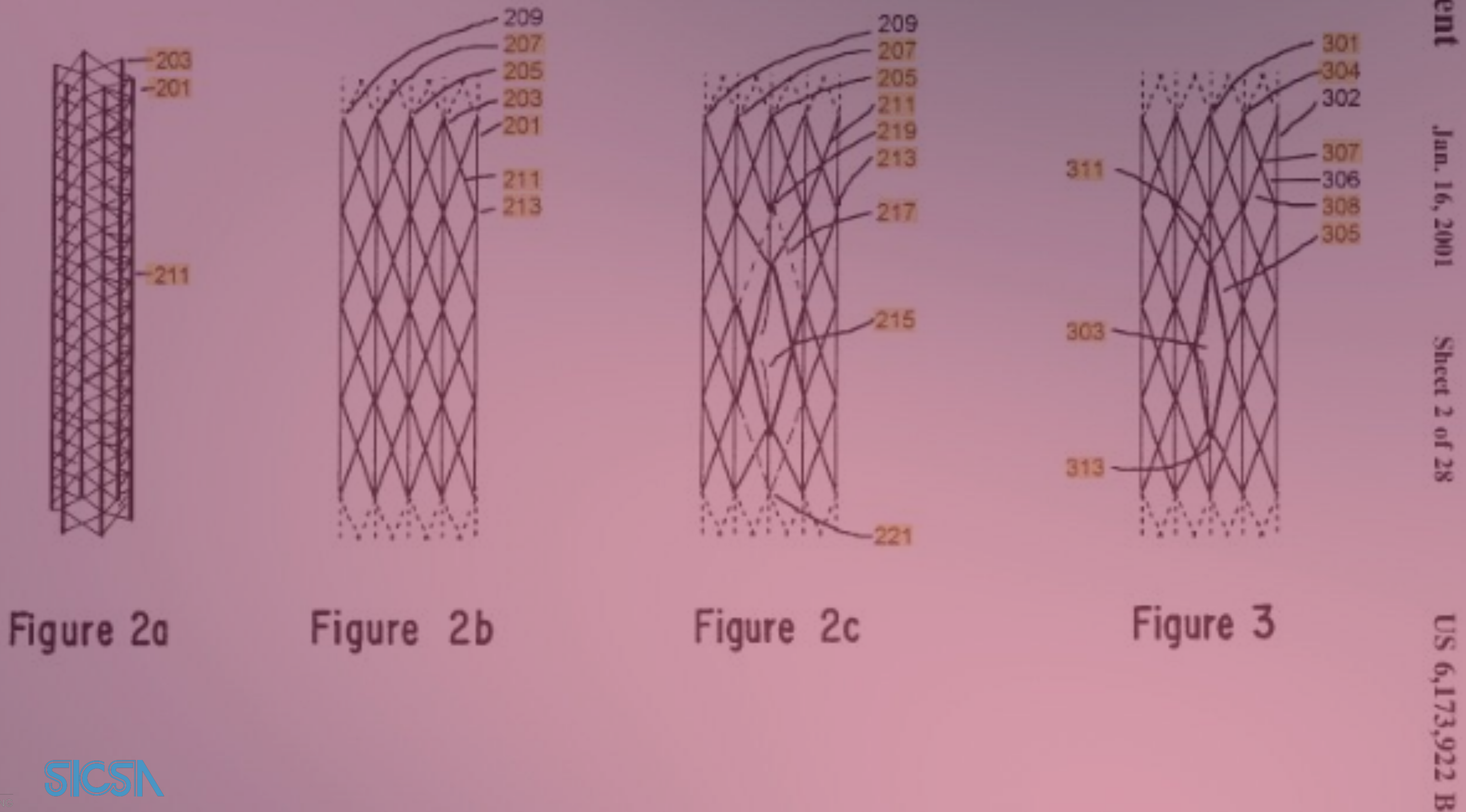


Figure 2a Figure 2b Figure 2c Figure 3

ID	Element		Cost (million)	Quantity	Total cost (million)	Mass (kg)
1	Crew Dragon		$310	2	$620	24000
2	Prichal (UM) module		$200*	1	$200*	4000
3	Progress MS		$300*	1	$300*	3290
4	Launch	Soyuz 2-1b (UM + Progress)	$80	1	$80	-
5		Falcon 9	$62	2	$124	-
6	Development Analysis, Integration, and testing		$100*	-	$100*	-
7	Sustaining operations		$100*	-	$100*	-
8	Grand Total				$1524	31290

Spin up calculations for static radius @ 10 m

Assumptions:

- The dragons are already at 10 m radius before start of spin-up. Radius of spin, r = 10 m
- Centripetal acceleration to be generated= 1g
- Therefore, Tangential velocity to be generated, a_t = m/s
- Time taken to spin up to enTend state, dt= 1200 sec (20 mins)
- Mass of Dragon 1, m_{d2} = Mass of Dragon 2, $m_{d1} = m_d$ = 12,000 kg
- Central hub is a solid sphere of mass, m_{ch} = 7290 kg and radius, r_{ch} = 2.5 m
- Thrust provided by augmented thruster, $F_a = F_1 = F_2$

Moment of Inertia of system, $I_{total} = \frac{2}{5} m_{ch} r_{ch}^2 + 2 m_d r_d^2$ ($MI_{sphere} + MI_{two\ body\ system}$)

= 18,225 + 2,400,000

= 2,418,225 kgm^2

Tangential acceleration, $a_t = r\,\alpha$

Angular acceleration, $\alpha = a_t / r$

$= (dv_t/dt) / r$ = (10 m/s / 1200 s) / 10 m= 1/1200 rad/s^2

Torque = $I_{total} \times \alpha$

= 2015 kgm^2/s^2

Also, Torque = $r_1F_1 + r_2F_2 = 2rF$

Therefore, thrust required by engine, F_a = Torque / 2r

= 2015 / 20

= 100 kgm/s^2

Spin up calculations for pre-deployed radius to 10 m in 20 mins.

Augmenting the KDTU-80 thruster for the Progress MS as an example, as the spin thrusters on the crew dragons,

For the KDTU-80 on a Progress MS,
Maximum mass of fuel spent, $dm = (F \times dt) / I_{sp} \times g_0$
$= (2950 \times 890) / 302 \times 9.81$
$= 886$ kg

For the KDTU-80 when augmented on the crew dragons, to perform the procedure described on the previous page,
Mass of fuel spent, $dm_a = (F \times dt) / I_{sp} \times g_0$
$= (100 \times 1200) / 302 \times 9.81$
$= 40$ kg

Therefore, If we spend 40 kg of fuel during spin-up and another 40 kg for spin-down, and if we keep the same sized tanks and same specs,

No. of test operations possible before refueling = 886 / (40 x 2)
= 11

Spin up calculations for r = 40 m, spin up time = 10 mins

Augmenting the KDTU-80 thruster for the Progress MS as an example, as the spin thrusters on the crew dragons,

For the KDTU-80 on a Progress MS,
Maximum mass of fuel spent, $dm = (F \times dt) / I_{sp} \times g_0$
$= (2950 \times 890) / 302 \times 9.81$
$= 886$ kg

For the KDTU-80 when augmented on the crew dragons, to perform the procedure described on the previous page,
Mass of fuel spent, $dm_a = (F \times dt) / I_{sp} \times g_0$
$= (500 \times 600) / 302 \times 9.81$
$= \sim 100$ kg

Therefore, If we spend 100 kg of fuel during spin-up and another 100 kg for spin-down, and if we keep the same sized tanks and same specs,

No. of test operations possible before refueling = 886 / (100 x 2)
= ~5

Spin up calculations for r = 10 m, spin up time = 60 mins

Augmenting the KDTU-80 thruster for the Progress MS as an example, as the spin thrusters on the crew dragons,

For the KDTU-80 on a Progress MS,
Maximum mass of fuel spent, $dm = (F \times dt) / I_{sp} \times g_0$
$= (2950 \times 890) / 302 \times 9.81$
$= 886$ kg

For the KDTU-80 when augmented on the crew dragons, to perform the procedure described on the previous page,
Mass of fuel spent, $dm_a = (F \times dt) / I_{sp} \times g_0$
$= (43 \times 3600) / 302 \times 9.81$
$= \sim 50$ kg

Therefore, If we spend 50 kg of fuel during spin-up and another 50 kg for spin-down, and if we keep the same sized tanks and same specs,

No. of test operations possible before refueling = 886 / (50 x 2)
= ~9

Source: Adaptation in a rotating artificial gravity environment, James R. Lackner, Paul DiZio, 1998

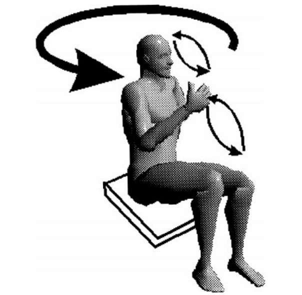


Fig. 1. Illustration of the scalloping motion experienced during voluntary pitch head movements and flexion–extension forearm movements made during body rotation. When subjects are rotating counterclockwise (heavy arrow) and pitch the head forward or extend the forearm they experience a rightward deviation (thin arrows) from the intended path (dotted lines) and the reverse when they raise the head or arm up. The scalloping motion is in the direction of the Coriolis force generated. It is exaggerated when the gravitoinertial force level increases and is almost abolished in microgravity, both for the arm and head.

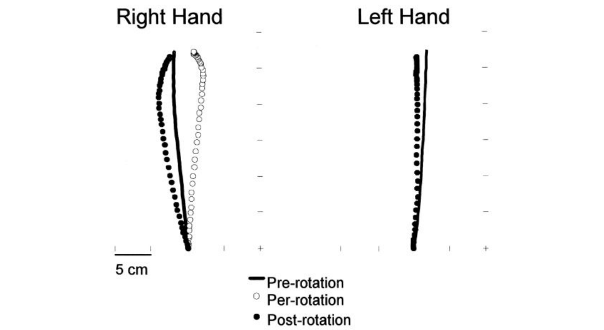


Fig. 3. Reaching movements made (averaged across eight subjects) in a study of intermanual transfer of adaptation to Coriolis forces in the rotating (counterclockwise) room. Same view, scale and sampling as in Fig. 2A. Baselines were established for both hands pre-rotation, 80 reaches were made per-rotation with the right hand to adapt it fully (not shown) to counterclockwise rotation. The initial post-rotation movements with the left hand went straight to a deviated endpoint. These movements mirrored the endpoint error but not the curvature of the initial per-rotation movements that had been made with the right hand. With subsequent left handed reaches (not shown) endpoint error rapidly diminished. When subjects first reached with the right hand after eight post-rotation movements of the left hand, their movements ended on target but arched symmetrically to the initial per-rotation reaches with the right hand.

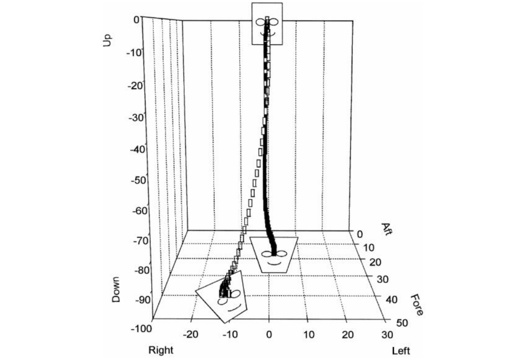


Fig. 5. Three-dimensional paths of typical pitch head movements made at 10 rpm counterclockwise in the rotating room. A point between the eyes was tracked at 100 Hz. The view is looking toward and slightly down on the subject, and the coordinate system is fixed relative to the subject's torso. The icons indicating head orientation are drawn smaller than the plotting scale. The solid rectangles are pre-rotation and the open rectangles per-rotation. Pre-rotation the path of the head is essentially straight with no lateral deviation and no rotation in yaw or roll. Per-rotation the head is initially deviated in the direction of the Coriolis forces generated and there is also rotation in yaw and roll. There is a rapid return to the median plane with additional per-rotation movements (not shown) but the roll orientation of the head does not adapt as quickly.

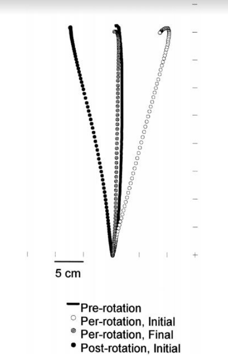


Fig. 4. Pointing movements of the leg (averaged across eight subjects) to a recently extinguished visual target on the floor of the rotating room. Same view, scale and sampling as Fig. 2A. Subjects stood and used their right leg, their head and waist were stabilized. Movement endpoints were initially deviated in the direction of the rightward Coriolis forces generated per-rotation (counterclockwise) and were deviated in mirror-image fashion post-rotation.

Test Response To Coriolis And Related Effects.

Test Response To Different Levels Of Gravity.

Test Response To Different Rates Of Angular Velocity And Radii.

Source: Artificial Gravity Evidence Report, Human Research Program, Human Health Countermeasures Element, Version 6, Gilles Clément, 2015

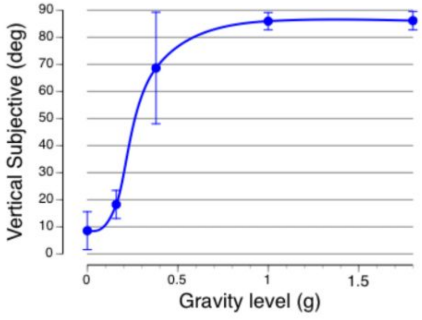


Figure 4. Dose-response curve of perception of verticality versus gravity level in parabolic flight. Mean of 6 subjects, 15-60 trials per subjects. Subjects lying on their side were able to accurately align their subjective vertical with the gravitational vertical for gravity levels ranging from 0.3 g to 1.8 g. Below 0.3 g they aligned their subjective vertical with their long body axis. Adapted from Winkel et al. (2012).

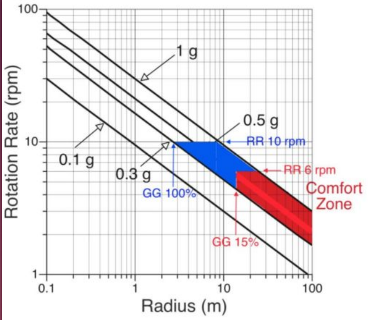


Figure 7. The rotation rate is plotted as a function of the radius of rotation for four gravity levels. Slow rotation rooms studies performed in the 1960s referred to the "comfort zone" as the red area delimited by gravity levels ranging from 0.3 g to 1 g, rotation rate < 6 rpm, and gravity gradient GG < 15% (radius > 12 m). However, recent data indicate that these limits are overly conservative: rotation rates of up to 10 rpm can be tolerated with incremental exposures, and large gravity gradient during intermittent short-radius centrifugation does not seem to be a critical factor (blue area).

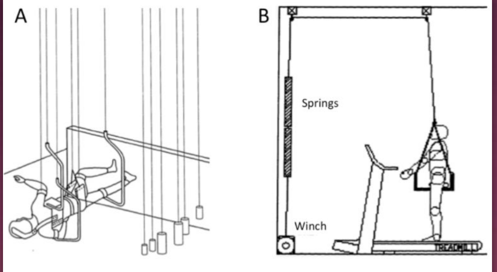


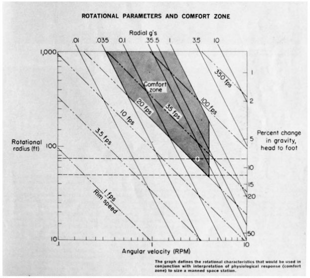
Figure 9. A. Body incline suspension system. The cables are attached to a crane located 10-20 m above the subject lying on his/her side. B. Body suspension system of an upright subject with cables, springs, and a bicycle harness. Adapted from Wu (1999).

Test Response To Coriolis And Related Effects.

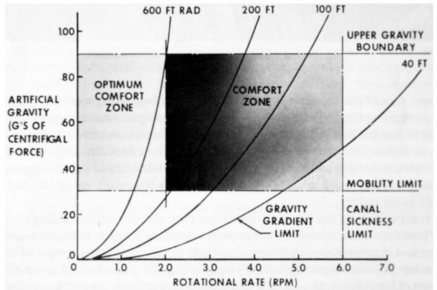
Test Response To Different Levels Of Gravity.

Test Response To Different Rates Of Angular Velocity And Radii.

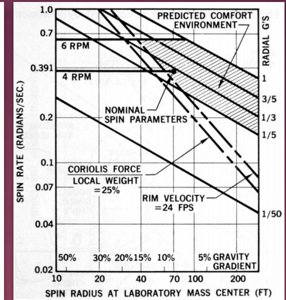
Source: Space Settlement Population Rotation Tolerance, Al Globus, Theodore Hall, 2017



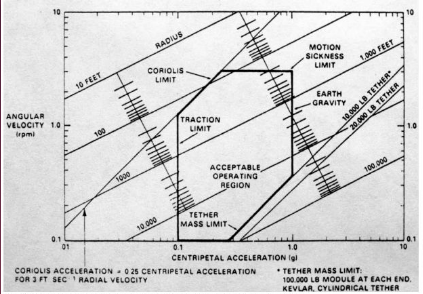
Comfort chart [Hill 1962]. At 1g this chart suggests that rates up to 4 rpm are in the comfort zone. (Note that, between 1 and 2 rpm, and between 2 and 3, there are intermediate tick marks corresponding to approximately 1.5 and 2.5.)



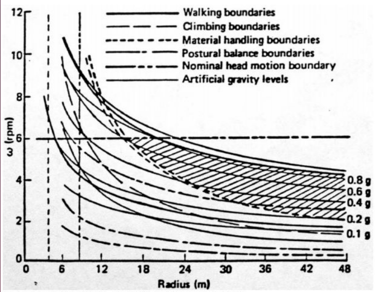
Comfort chart [Gilruth 1969]. Here 6 rpm is the chosen limit to comfort.



Comfort chart [Gordon 1969]. Here 6 rpm is the limit of comfort at 1g.



Comfort chart [Cramer 1983]. Here 3 rpm is the motion sickness limit.



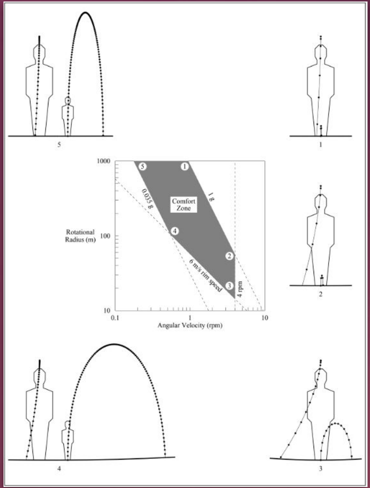
Comfort chart [Stone 1973]. Again, 6 rpm is the limit of comfort.

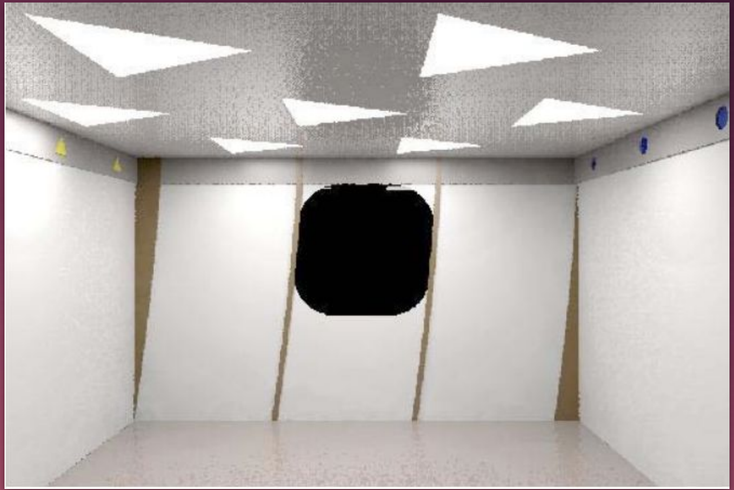
Test Response To Coriolis And Related Effects.

Test Response To Different Levels Of Gravity.

Test Response To Different Rates Of Angular Velocity And Radii.

Source: Artificial Gravity And The Architecture Of Orbital Habitats, Theodore W. Hall,1999





Test Response To Coriolis And Related Effects.

Test Response To Different Levels Of Gravity.

Test Response To Different Rates Of Angular Velocity And Radii.

ID	Test Objectives	Task	Duration (mins)	RPM	Radius
T0	In a free flying but non-spinning condition, Confirm the following systems work ● ECLSS ● GNC ● Power systems ● Propulsion and AAC	Undock Move to TOZ Park Move to ISS Dock	- TBD 20 (?) TBD -	-	-

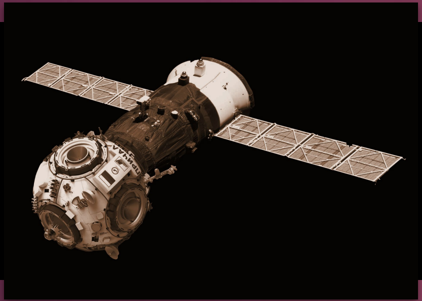
ID	Test Objectives	Task	Duration (mins)	RPM	Radius
T1	In a free flying and spinning condition. Confirm the following systems work • ECLSS • GNC • Power systems • Propulsion and AAC • Spin up and spin down system • Tethering system	Undock	-	TBD	TBD
		Move to TOZ	TBD		
		Spin Up	TBD		
		Perform tests	20		
		Spin down	TBD		
		Move to ISS	TBD		
		Dock	-		

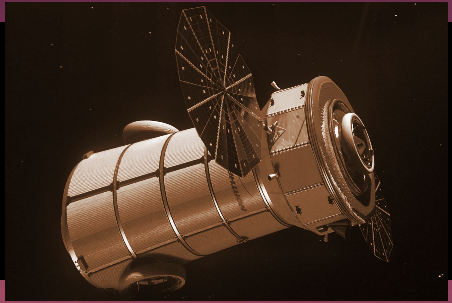
ID	Test Objectives	Task	Duration (mins)	RPM	Radius
T2 T3 T4 …	In a free flying and spinning condition. Iterate and improve the following systems • ECLSS • GNC • Power systems • Propulsion and AAC • Spin up and spin down system • Tethering system	Undock	-		
		Move to TOZ	TBD		
		Spin Up	TBD		
		Perform tests	Varied	Varied	Varied
		Spin down	TBD		
		Move to ISS	TBD		
		Dock	-		

<table>
<tr><th>ID</th><th>Test Objectives</th><th>Task</th><th>Duration (mins)</th><th>RPM</th><th>Radius</th></tr>
<tr><td rowspan="7">P1</td><td rowspan="7">Perform short term tests. In the framework of papers listed:
○ Jump and drop tests
○ In-place motion tests
○ Lateral movements tests
■ prograde
■ retrograde
■ parallel to spin axis</td><td>Undock</td><td>-</td><td rowspan="7">TBD</td><td rowspan="7">TBD</td></tr>
<tr><td>Move to TOZ</td><td>TBD</td></tr>
<tr><td>Spin Up</td><td>TBD</td></tr>
<tr><td>Perform tests</td><td>20</td></tr>
<tr><td>Spin down</td><td>TBD</td></tr>
<tr><td>Move to ISS</td><td>TBD</td></tr>
<tr><td>Dock</td><td>-</td></tr>
</table>

ID	Test Objectives	Task	Duration (mins)	RPM	Radius
P2 P3 P4 …	Perform short term tests. In the framework of papers listed: ○ Jump and drop tests ○ In Place motion tests ○ Lateral movements tests ■ Prograde ■ Retrograde ■ Parallel to spin axis	Undock	-		
		Move to TOZ	TBD		
		Spin Up	TBD		
		Perform tests	Varied	Varied	Varied
		Spin down	TBD		
		Move to ISS	TBD		
		Dock	-		

	Vectran		Toro		Spectra		G/T Composite braid	
Factor of Safety	size (in)	total tether mass (kg)	size (in)	total tether mass (kg)	size (in)	total tether mass (kg)	size (in)	total tether mass (kg)
2	1/2	54.8	1/2	36.4	9/16	47.2	3/4	97.2
5	3/4	166.4	7/8	110	1	139.2	7/8	121.6
10	1-1/8	274.8	1-1/8	180.4	1-1/2	307.6	1-5/16	292.4





Cost, Propulsion, Docking Ports, Operational Status