Orbital Energy Management –

Or Orbital Refueling that Works

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Define The Problem

- There is an upper limit to Mass/Volume that can be launched from Earth: 52 MT (Falcon 9 Heavy) to 140 MT (Falcon XX).
- Any vehicle that goes beyond Low Earth Orbit will have a large percentage of the mass as propellant.
- Therefore, the practical limit of a single launch from the surface of Earth to Mars is 25 percent of the LEO mass (one way).
- Therefore our theoretical payloads to Mars are 13 – 35 MT.

- NOTE: Mars Direct reduces RETURN mass, meaning you can do more with less.
- This talk is about getting more mass away from LEO.

Bounding the Solution Set

There are three options for getting beyond LEO with more mass…

- **On Orbit Assembly**
- **On Orbit Fueling**
- **Increased Propellant Efficiency (Ion Drive, Nuclear)**

On Orbit Assembly means more mass to move, not more propellant to move it.

Ion drive means one of the following:

- **2 years to Mars – not acceptable for a crew.**
- **A very powerful energy source, which would also add mass and complexity.**

A nuclear engine would be billions in development prior to launch

Propellant Types & Reasons

Rockets have a practical speed limit: Twice the exhaust velocity

Different propellants have different exhaust velocities.

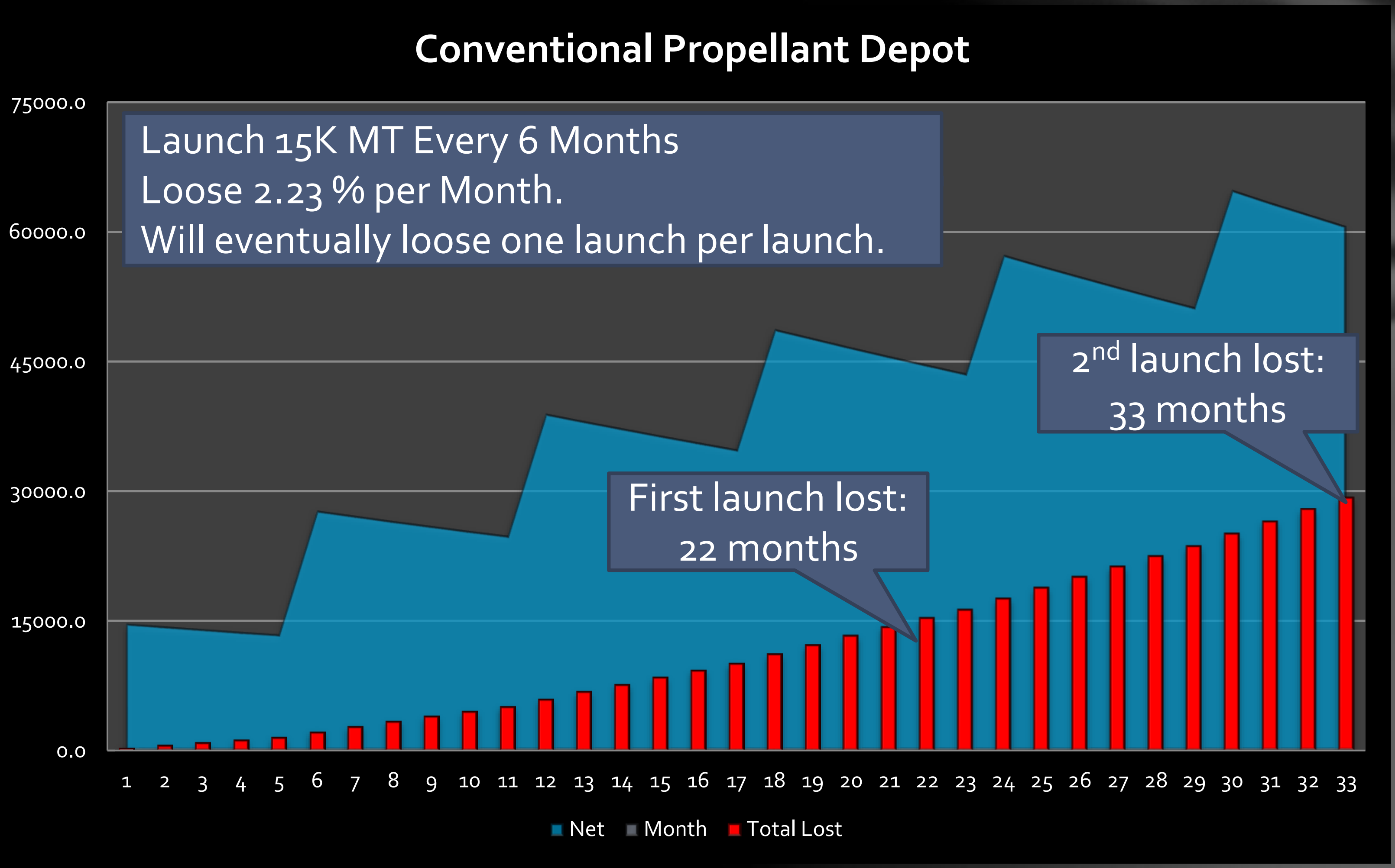
Kerosene (RP-1) gets payloads to orbit (Falcon), but would be limited in getting them to the moon or escape velocity.

Best propellant for Earth Departure is hydrogen (LH_2) and oxygen (LOX)

But Hydrogen…

- Escapes any container over time
- Embrittles metals in the process
- Must be kept close to absolute zero
- Occupies a very large volume for a very low mass.
  - This makes the container heavy, because it is large, thick, and well insulated.
- Any large vehicle in LEO for a long period is subject to debris strikes.
- The risk is increased because a propellant depot by definition is a thin skinned flying bomb.

Leakage Versus Launch



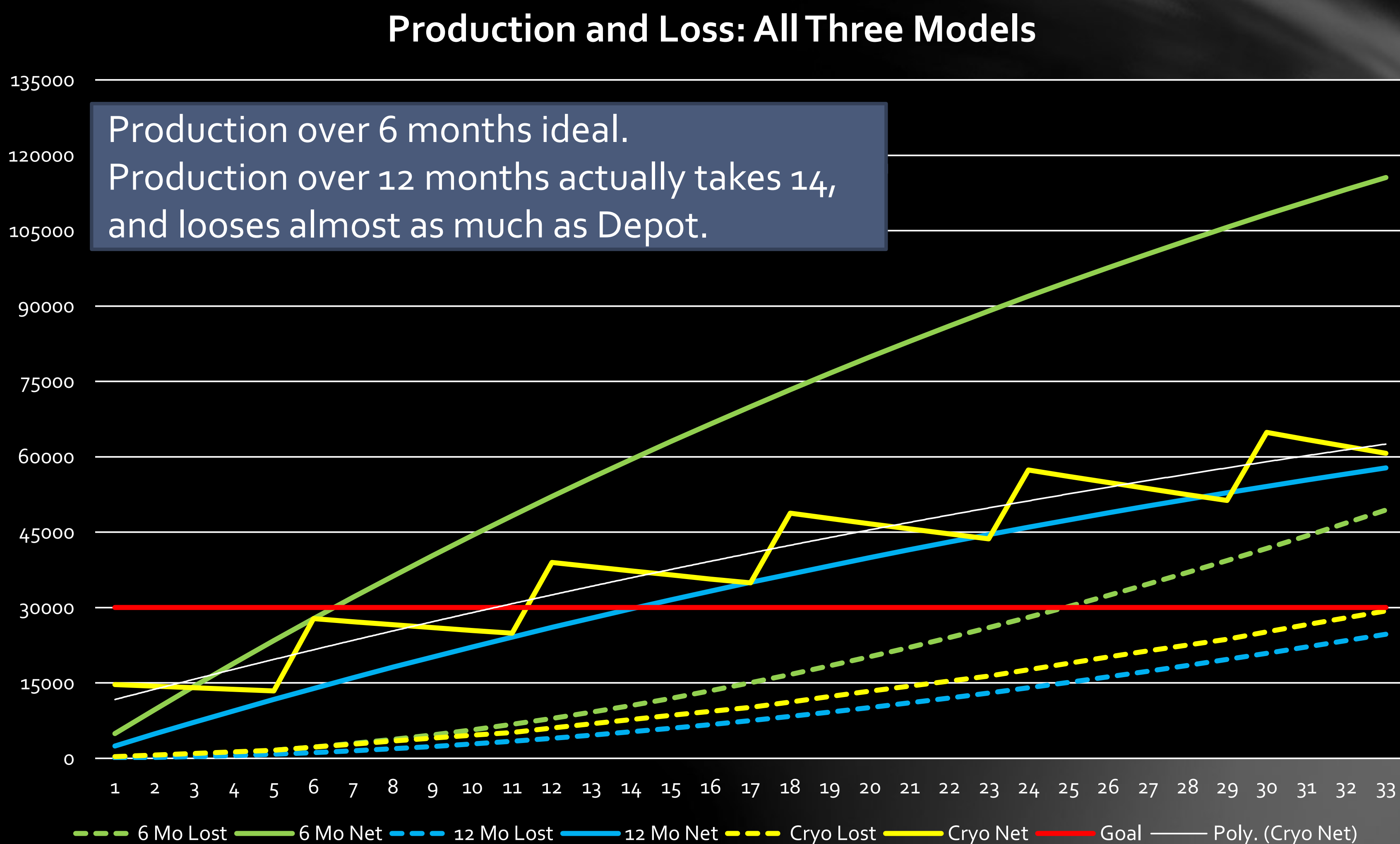
Solution: Energy Management Station

Conventional Propellant Depot	Energy Management Station
Hydrogen Leakage, Risk with launch, High volume tank at launch	Launch water, Create Hydrogen/Oxygen when needed. Decouples surface launch schedule from Earth Departure launch window.
Hydrogen temperature requires refrigeration to limit loss	Water can be left as water or shaded to form ice.
Orbital Debris + Thin tanks + Volatile Propellants = Very high risk of explosion.	Ice can be reinforced with a matrix to be harder than concrete Non explosive, but will turn to steam if enough energy imparted.
Engine requires 6 oxygen to 1 hydrogen by mass	Water is 8 oxygen to 1 hydrogen by mass
Single propellant mix	Use leftover 2 oxygen with RP-1 and/or Methane also stored at station.

Energy Management Station

Idealized 100 MT of water – size of Bigelow Aerospace Sundancer		
Notional Model	BA Sundancer shell	180 M3 available
Water Tanks	Bladders in inflated station space	100 M3 100,000 kg
Yield	Hydrogen Mass/Volume	11,190 kg, 40.0 M3
	Oxygen Mass/ Volume	88,810 kg, 77.9 M3
LOX/LH2 Engine	Required Oxygen	67,250 kg, 59.0 M3
LOX:LH2 Ratio	6.01:1	78,441 kg propellant at ISP 448
Leftovers	Remaining Oxygen	21,559 kg, 18.9 M3
Option 1	Methane	6,341 kg, 15.0 M3
O:CH4 Ratio	3.40:1	27,900 kg propellant at ISP 372
Option 2	RP-1 (Kerosene)	8,422 kg, 10.4 M3
O:RP-1 Ratio	2.56:1	29,981 kg propellant at ISP 353

Propellant Production Versus Depot



Production and Recycling

Launch Windows:

- **Near Earth Asteroids: Minutes Per Decade**
- **Mars: 2 Weeks every 26 Months**

For conventional Propellant Depot…

- **Missing a launch window is a $100 billion financial disaster.**
- **Would have to have a more risky back-up mission available to avoid loss if primary mission missed.**

For Energy Management Depot…

- **Run Hydrogen/Oxygen through fuel cell, generate power**
- **Convert back to water with minimal hydrogen loss**

EMS Tied to Space Station

Benefit	Details
Cosmic Ray Protection	4 meters of ice will block cosmic rays as well as Earth's atmosphere.
Debris Protection	Debris has to get through equivalent of concrete several meters thick to get to crew module, provided the tank is between crew module and direction of strike.
Life Support	Carbon Dioxide can be feedstock for oxygen, methane production, or simply recycled back to crew oxygen.
Reboost	Small quantities of propellant can power engines for maintaining orbit. Will be needed anyway for EMS.
Power	When not making propellant, station's solar panels available for attached station power. Added power for customers.

Medium Scale Station

Water Tanks	100 M3 100 MT	Sundancer: 180 M3 volume 8.7 M long, 6.3 M diameter, 8.6 MT Mass, complete
Hydrogen	Remaining: 10,359 kg	Produced: 11,190 kg, Lost: 831 kg 37.0 M3
Cryo Propellant	Oxygen: 62,258 kg Total: 72,617 kg	54.6 M3
Time Demands	6 Months	117 Kw*h/Day
Power Demands	150.5 M2 Solar Array Converter, plus nom.	ISS Solar Array 375 M2 per wing, 8 wings.
CH_4 Option	Methane: 7,809 kg Oxygen: 26,552 kg	18.4 M3 23.3 M3
RP-1 Option	RP-1: 10,372 kg Oxygen: 26,552 kg	12.9 M3 23.3 M3

Delta V, Medium Station

	Arrival mass scaled to departure mass payload	
	Lunar Mission	**Mars Mission**
Cryo Stage:	**47,000 kg LEO > Lunar Orbit**	**47,700 kg Departure + Corrections**
Methane Stage:	**28,200 kg Lunar Landing**	**21,700 kg Mars Orbit Entry** **38,400 kg Mars Landing**
	15,577 kg Propellant Left Over	**34,361 kg Propellant Left Over**
RP-1 Stage:	**27,440 kg Lunar Landing**	**20,800 kg Mars Orbit Entry** **37,900 kg Mars Landing**
	17,372 kg Propellant Left Over	**27,192 kg Propellant Left Over**

RESULT:

- **Station is able to transport a copy of itself, or itself, to Moon or Mars**
- **Allows modular system with Falcon 9 or Falcon 9 Heavy to launch as much to Mars Surface as Falcon XX (140 MT to LEO)**

Launch Schedule: Station + 160 MT propellant

Launch 1	Launch 2	Launch 3	Launch 4	Launch 5
Falcon 9H	Falcon 9H	Falcon 9H	Falcon 9H	Falcon 9H
Main Station 20 MT	RP-1/ CH_4 40 MT	Water 40 MT	Water 40 MT	Water 40 MT
Solar Array 5 MT	Tank 10 MT	Tank 10 MT	Tank 10 MT	Tank 10 MT
Docking Frame 5 MT				
Tug? 15 MT				
Total: 45 MT	Total: 50 MT	Total: 50 MT	Total: 50 MT	Total: 50 MT
Station/Tug installed	20 MT RP1 20 MT CH_4 2 small tanks	40 MT Water 1 Cryo Tank	80 MT Water 2 Cryo Tanks	120 MT Water 3 Cryo Tanks

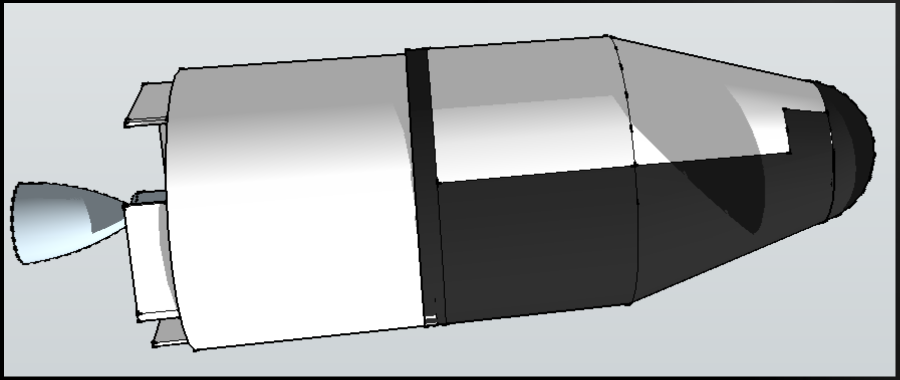
Falcon Tanker/Tug Concept

Falcon 9 Heavy upper stage plus Dragon-derived RCS/etc.

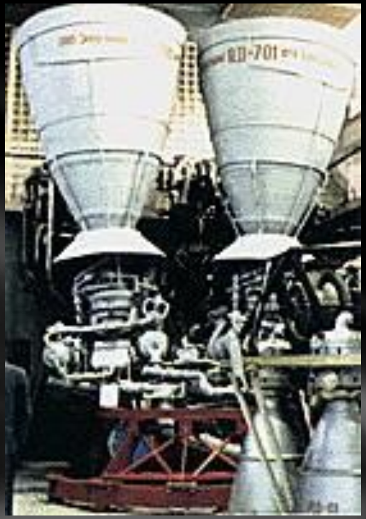
Flown as one piece, with second stage tanks plus nose tank for water/hydrogen. Extend rear tanks if appropriate.

Propellant and water transferred to station on arrival.

- Can be built to reenter and land. Entire stage reused.
- Alternate version can remain on station and act as departure stage. May use Raptor engine instead.

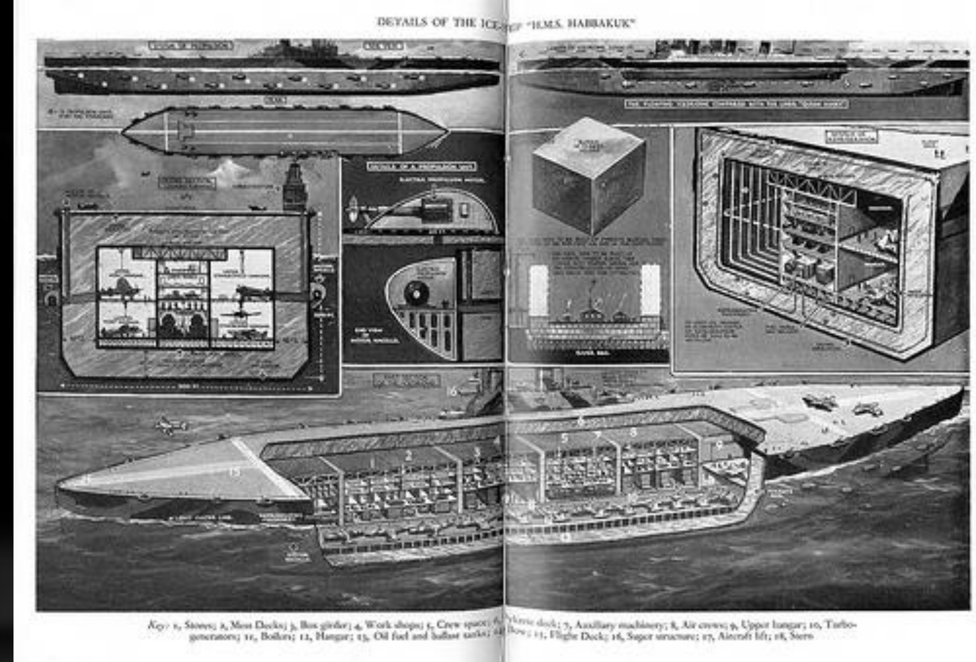


Tri-Propellant Designs



- This would give best of both systems by starting with high-density RP-1 and slowly shifting to high-speed LH2.
- Single engine RP-1/LOX/LH2 engines (RD-701) were developed in MAKS Russian mini-shuttle in the 1980's. Was test-fired 50 times.
- Aerojet has some of the technology (RD-0120TD).
- Would make effective single departure/arrival stage, leaving with LH2 and arriving with RP-1.
- If methane version built, reusable with ISPP for Return

What is “Pykrete”?



Reinforced Ice Composite

Original pykrete was
14 percent sawdust,
86 percent water.

Almost as strong as concrete, can stop bullets.

Original was a WWII Invention
of Geoffrey Pyke for building a huge aircraft
carrier out of ice for the British Royal Navy,
cooled with pipes (Project Habbakuk).

Remakes of pykrete have been made out of newspaper to
give a lattice structure like fiberglass – much stronger
than original. (Mythbusters, Ep 115, 2009)

Pykrete In Space, Non-Interactive

An optimized pykrete for this tank would have many gauze-like layers of spectra fabric between the fabric layers of the tank.

Each layer would stand off the one next to it to form a series of layers, possibly with a cross-matrix as well.

This allows the ice to be reinforced (similar to concrete rebar) without contaminating the water with an absorbent material.

Pykrete In Space, Interactive

An alternate approach would be to use an absorbent, strong matrix that would not chemically interact with the water.

Application of strong heat or low pressure would dry material completely.

Water Tanks – Membrane Pumps

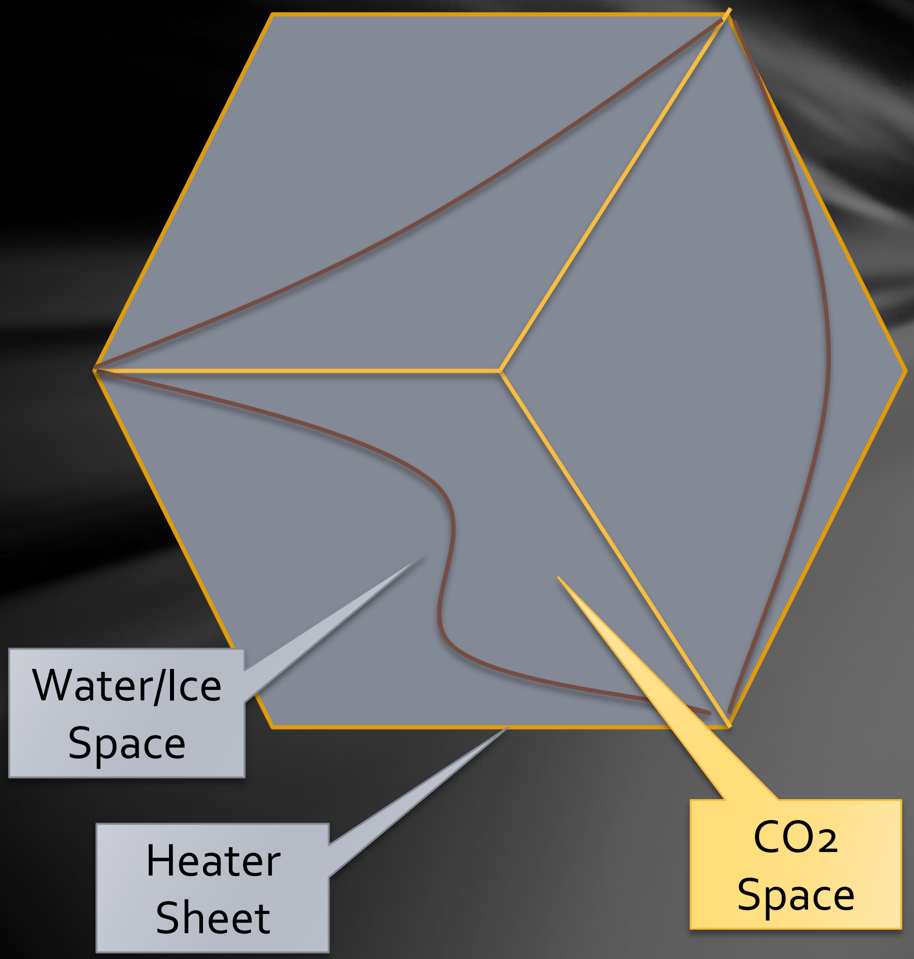
Tanks are diamond-shaped with membrane down middle.

Tank space initially filled from one side with CO_2 to fill full volume of the diamond.

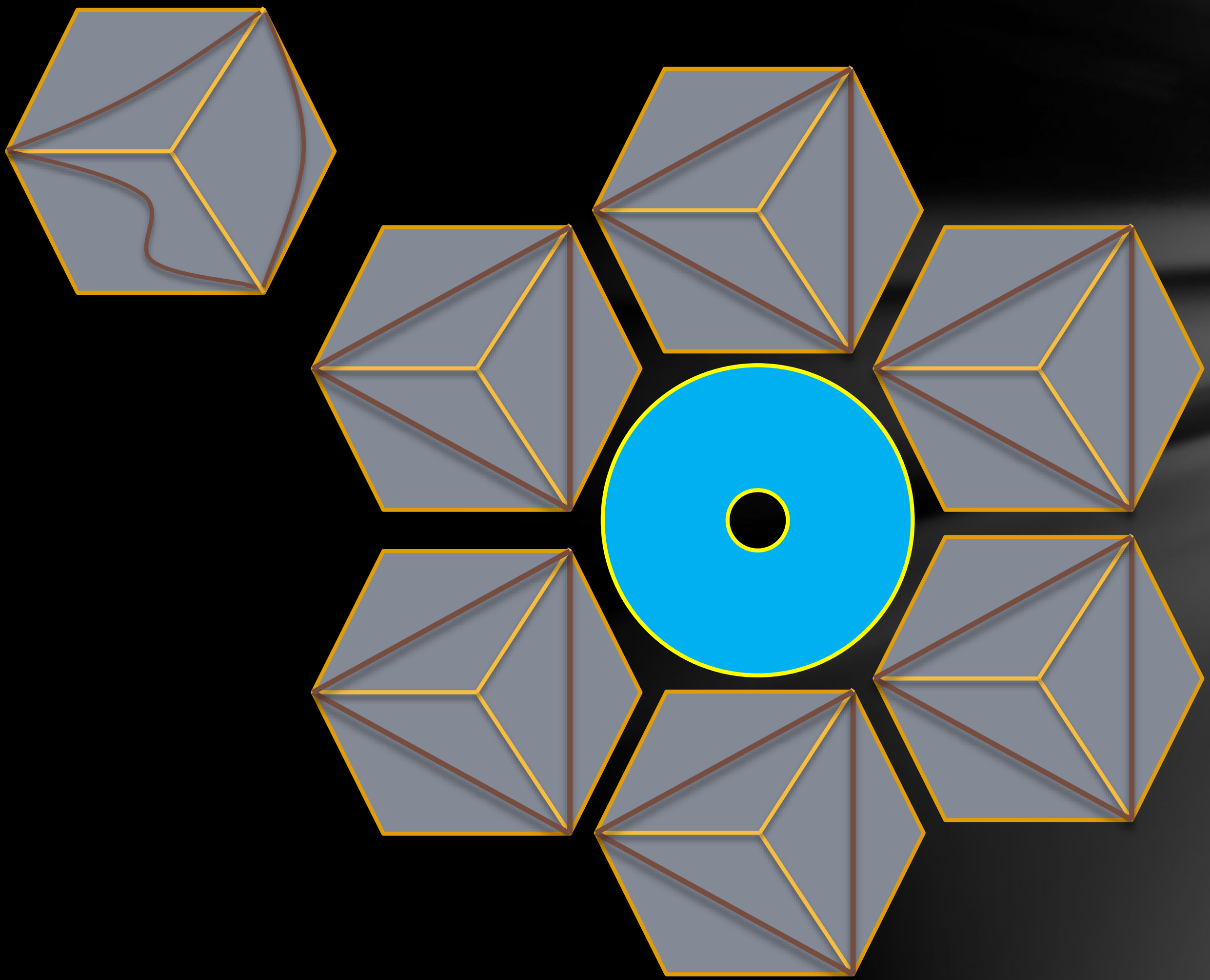
As water added to water side of membrane, CO_2 removed from gas side.

Allow enough space to freeze.

To pump water out, thaw and pump CO_2 in to squeeze tank.



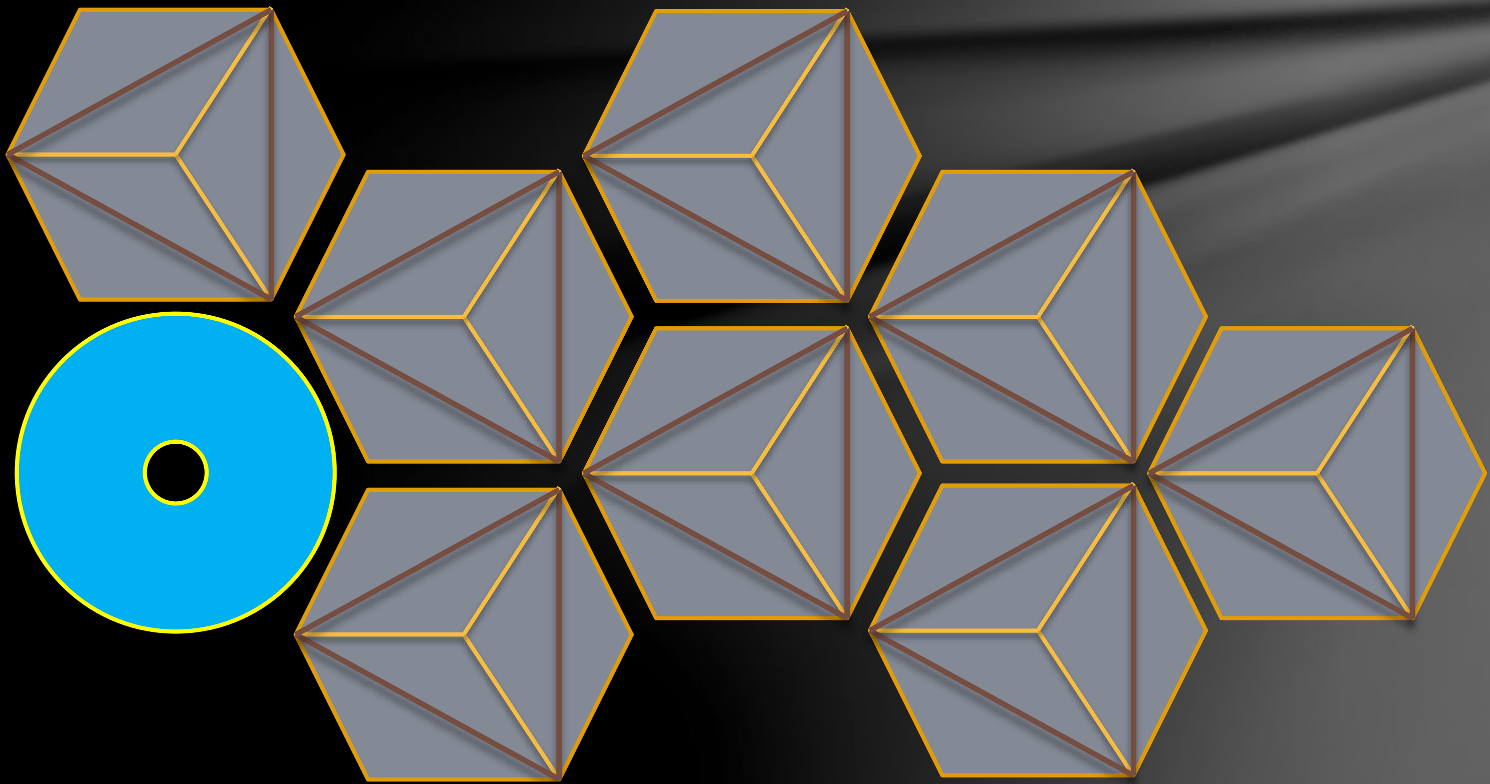
Water Tank Geometry



Infinite Expansion Matrix

Works efficiently with cylindrical tanks/habitats.

Can be made flat for surface bases, integration with trusses.



Foldable Tanks

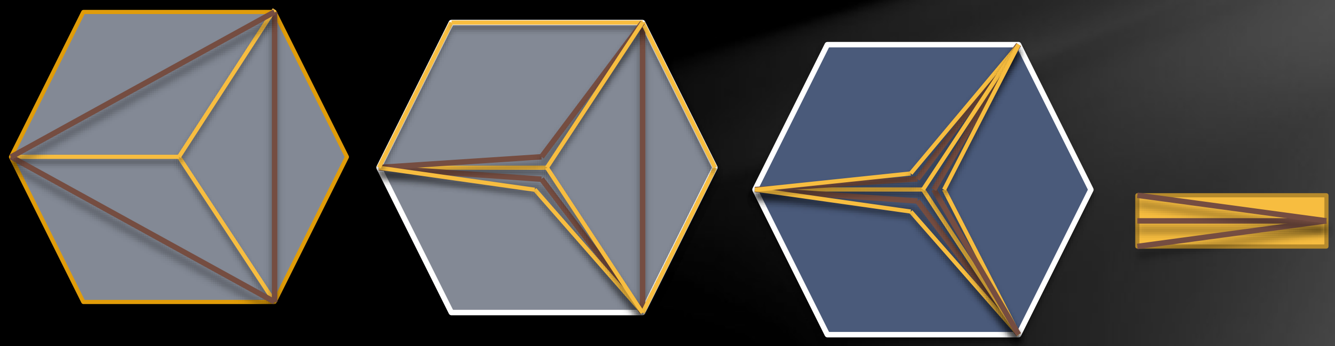
All layers the same shape.

To deflate a diamond tank, drain both tanks.

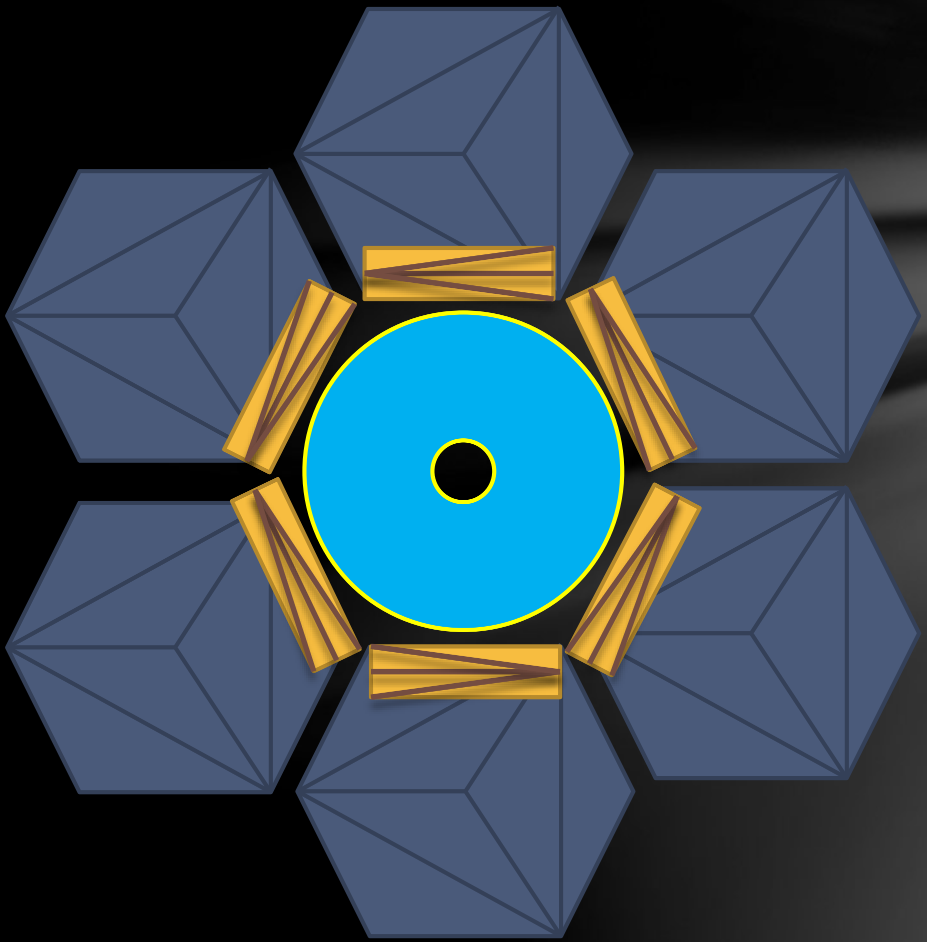
Result is V-shaped flat tube with bendable spine.

Fold all three tanks around center axis – single flat sheet.

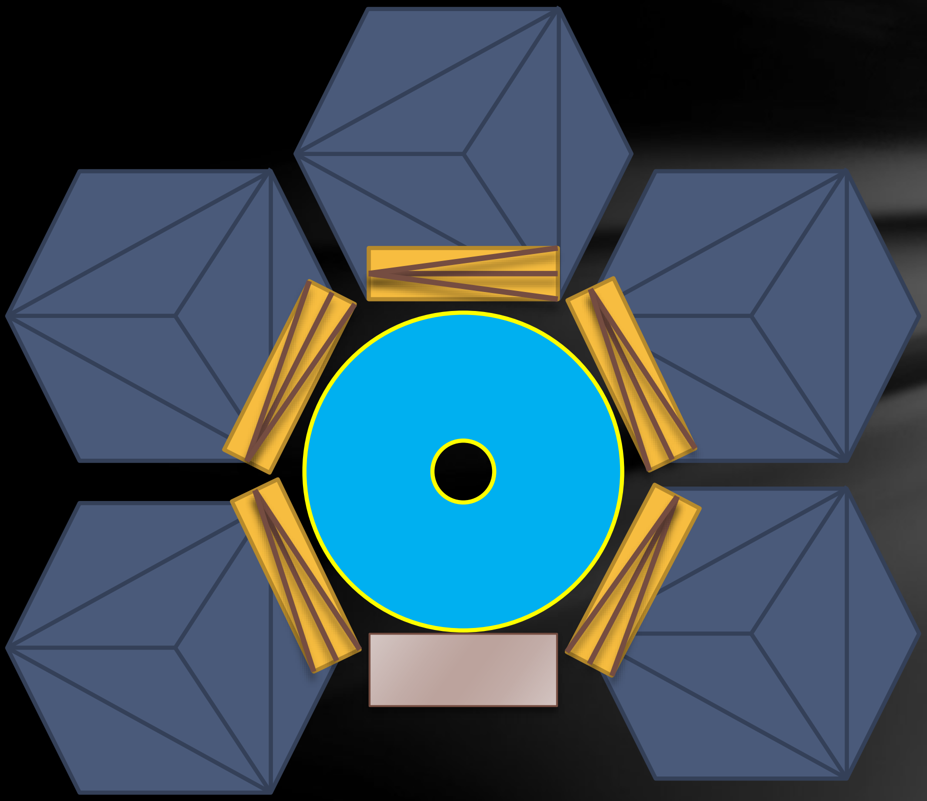
May be pushing it to roll sheet.

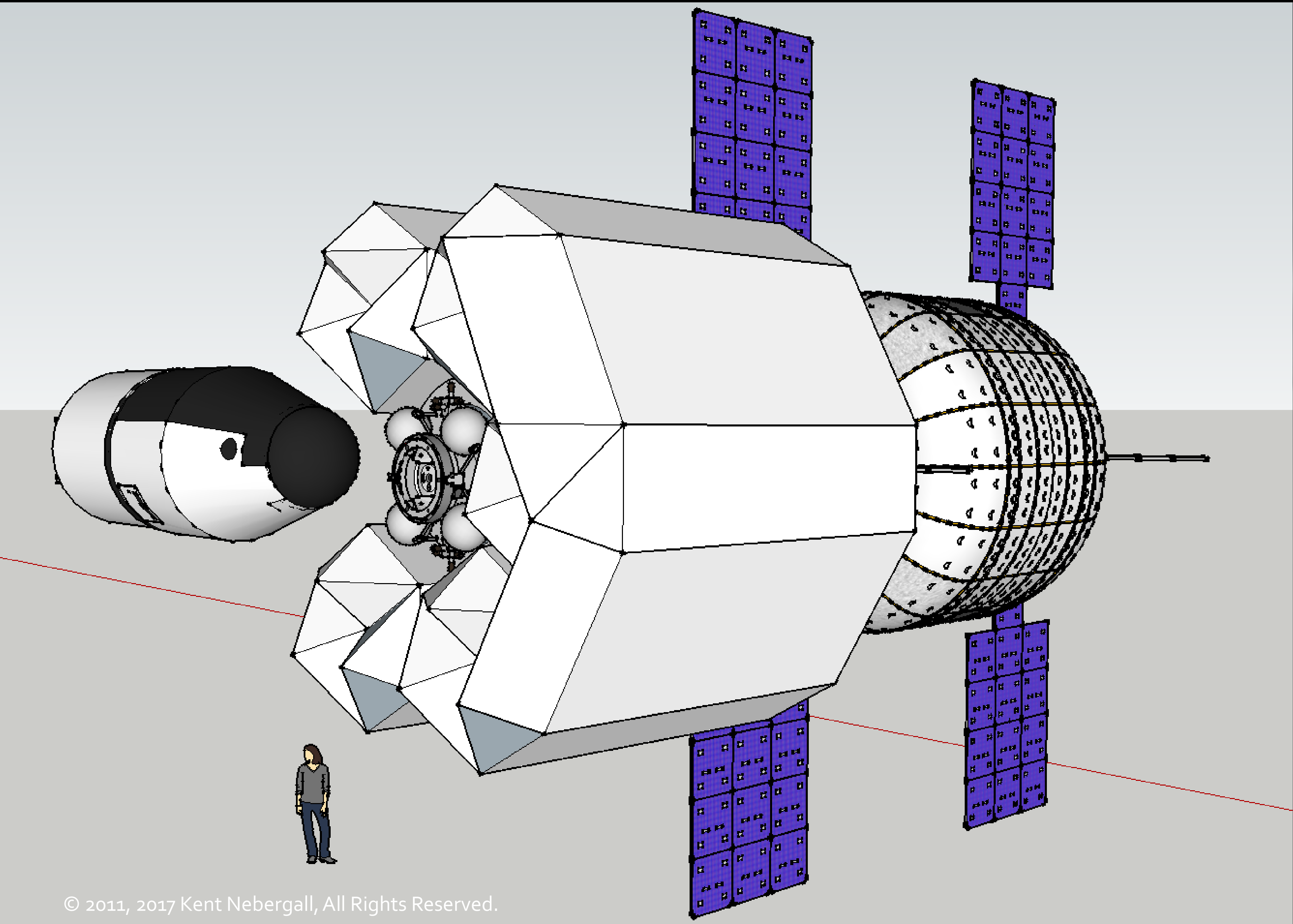


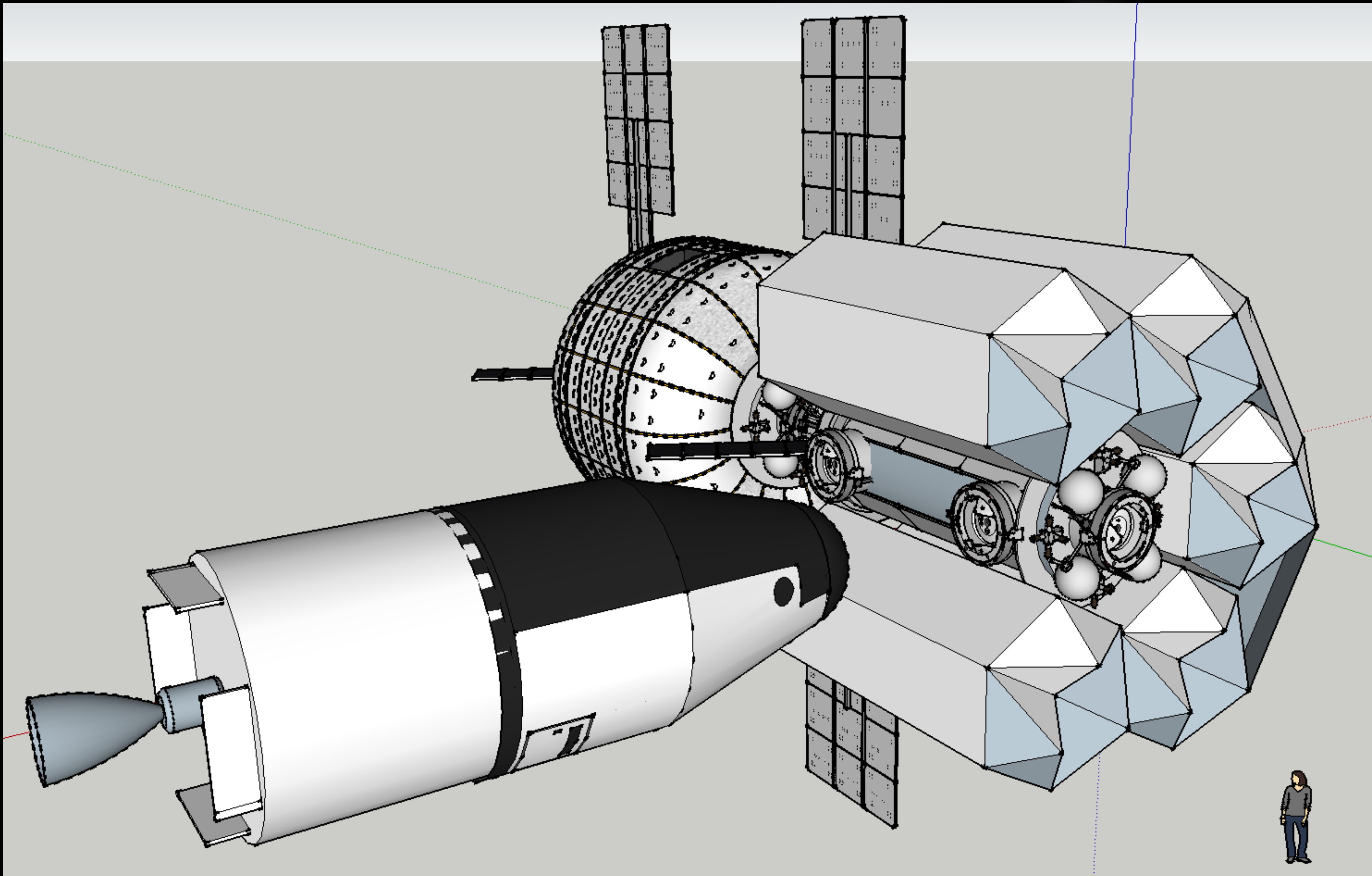
Preconstructed in Aeroshell

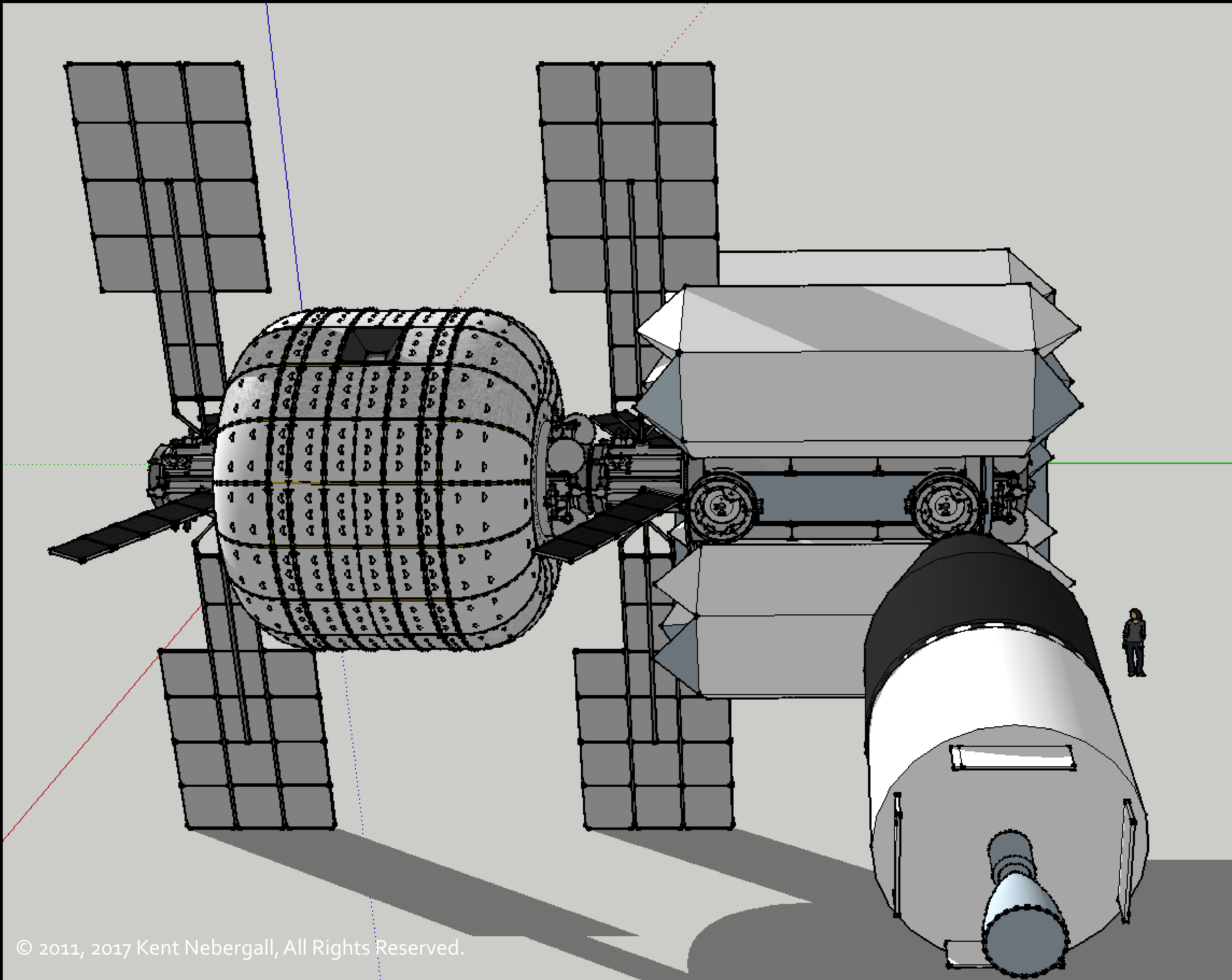


Structured for Docking

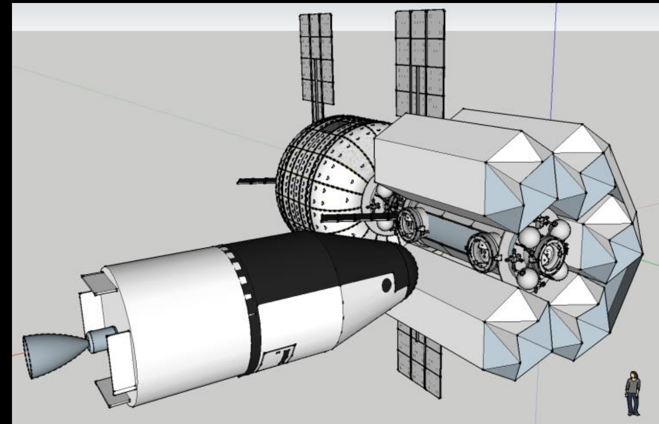


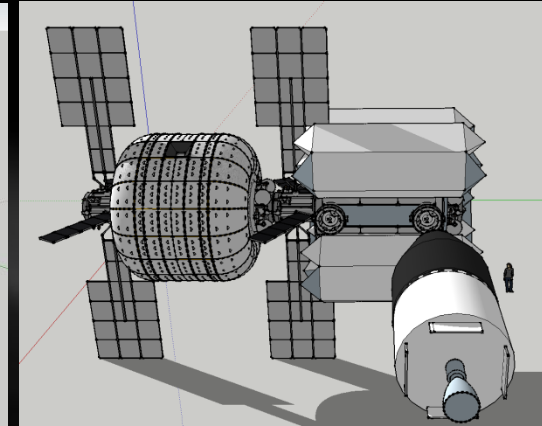






Results





	Water Tank	X 5 Water Tanks
Volume	60.5 M3	302.4 M3
Width	1.75 meter sides, 3.5 Meters total	10.5 meters plus gaps
Length	Core: 6.6 meters, Ends: 1 meter each	8.6 meters long

RESULT:

- Triple the design capacity
- Ample margins for membranes, structure, heaters, and pykrete elements
- Four docking ports with Sundancer core.
  Could double that with same tanks and BA330 core
- Modules could be wrapped around crew section for cosmic ray shelter
- Needs another solar panel- location to be determined.

Mars Shuttle

Mars Direct	Mars Shuttle
Develop Methane Engine	Develop Methane/Hydrogen Tri-propellant engine
Cryo Departure stage plus Near-empty ERV	Fuel Mars Shuttle with Hydrogen, Oxygen, Methane before LEO departure, with strap on tanks if needed.
Launch with cryo stage, Throw away cryo stage	Fire Mars Shuttle in hydrogen/ oxygen mode for departure Keep methane/oxygen for landing
Wastes departure stage	Solid from LEO to Mars Surface, and back to Mars orbit.
Brings crew to Earth, Throw away ascent stage	Could supply propellant to facility in Mars orbit. Be fully reusable at Mars.
NOTIONAL: Math not verified	