# Abstract #1740

### English

## Framework for Evaluating Economic Impact of Asteroid Resources

We report on the development of a framework for evaluating the impact of extraterrestrial resources on the cost of human operations in cislunar space. In our analysis we consider the development and operation of three alternative cislunar transportation networks, each based on fully reusable launch and in-space transportation vehicles such as planetary landers, upper stages, and Orbit Transfer Vehicles (OTVs). One of the networks is based on Earth supplied propellant, one on asteroid provided propellent focussing on LOX-LM systems, and one which uses asteroid derived water based solar thermal propulsion for in space transportation and LOX-LM systems for landed systems. Missions considered included development and ten years of operation of a lunar orbiting outpost; development and ten years of operation of a lunar surface outpost, human exploration of Near Earth Objects (NEOs), and human exploration of Mars through four Mars mission opportunities. Our analysis suggests a savings in excess of $200B over a twenty year program, enough to bring NASA's ambitions for human exploration within a politically feasible total agency cost cap of approximately $20B/yr. Peak year funding without large scale ISRU is found to be approaching $30B/yr in 2017 dollars for just the human exploration program even with the benefit of fully reusable systems and commercial development approaches. For the asteroid ISRU case, peak year human exploration program funding never exceeds $10B/yr. To independent cost models were applied and found to give results that agree within 20 percent. These architectures may also enable massive new space industries including asteroid mining of minerals, space adventure travel through cislunar space, space solar power, and massive increases in communications satellite applications.

### French

## No abstract title in French

No French resume

### Author(s) and Co-Author(s)

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# Profile of Dr. Joel Sercel

## General

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Preferred Language: [Language not defined]

## Addresses

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## Biographies

**Biography submitted with the abstract**

Joel C. Sercel, PhD, is the Founder and Chief Engineer of the Trans Astronautica Corporation (TransAstra), a new kind of aerospace company dedicated to the belief that humanity will thrive as a species once we make the leap and homestead the solar system. With the recent swarm of technological breakthroughs in information systems, manufacturing, sensor systems, and robotics now is the time to move from dreaming about homesteading space, to doing it. TransAstra is building the technology to provide in-space transportation and related services with a fleet of reusable space tugs supplied by propellant derived from asteroid and lunar resources. Our first customer will be NASA, but soon after we will support the new asteroid mining industry for returning valuable resources to the Earth. Space tourism, space solar power, and then space based manufacturing will follow quickly. Dr. Sercel has decades of experience developing advanced technology and innovative products in fields ranging from aerospace and defense to software and robotics. In addition to his private sector work, Joel spent 14 years at JPL and taught systems engineering and space mission and satellite design at the graduate level at Caltech. Dr. Sercel led the conception and definition of the NSTAR ion propulsion system currently in use on the Dawn spacecraft in orbit around the asteroid Ceres. Dr. Sercel received his PhD and master's degrees in Mechanical Engineering from the California Institute of Technology with a doctoral dissertation in plasma physics as applied to space propulsion. His bachelor's degree was in Engineering Physics from the University of Arizona.

**Biography in the user profile**

## Collaborators

**Author(s) and Presenter(s)**

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Presenter(s):

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# Stepping Stones: Economic Analysis of Space Transportation Supplied From NEO Resources
## - Summary of Preliminary Results -


TRANS ASTRA

Summary Presentation on Grant No NNX16AH11G Funded Under Economic Research for Space Development

Technical Officer: Lynn D. Harper PhD

PI: Joel C. Sercel, PhD
TransAstra Corporation

Winter 2016

A Framework for Considering Options

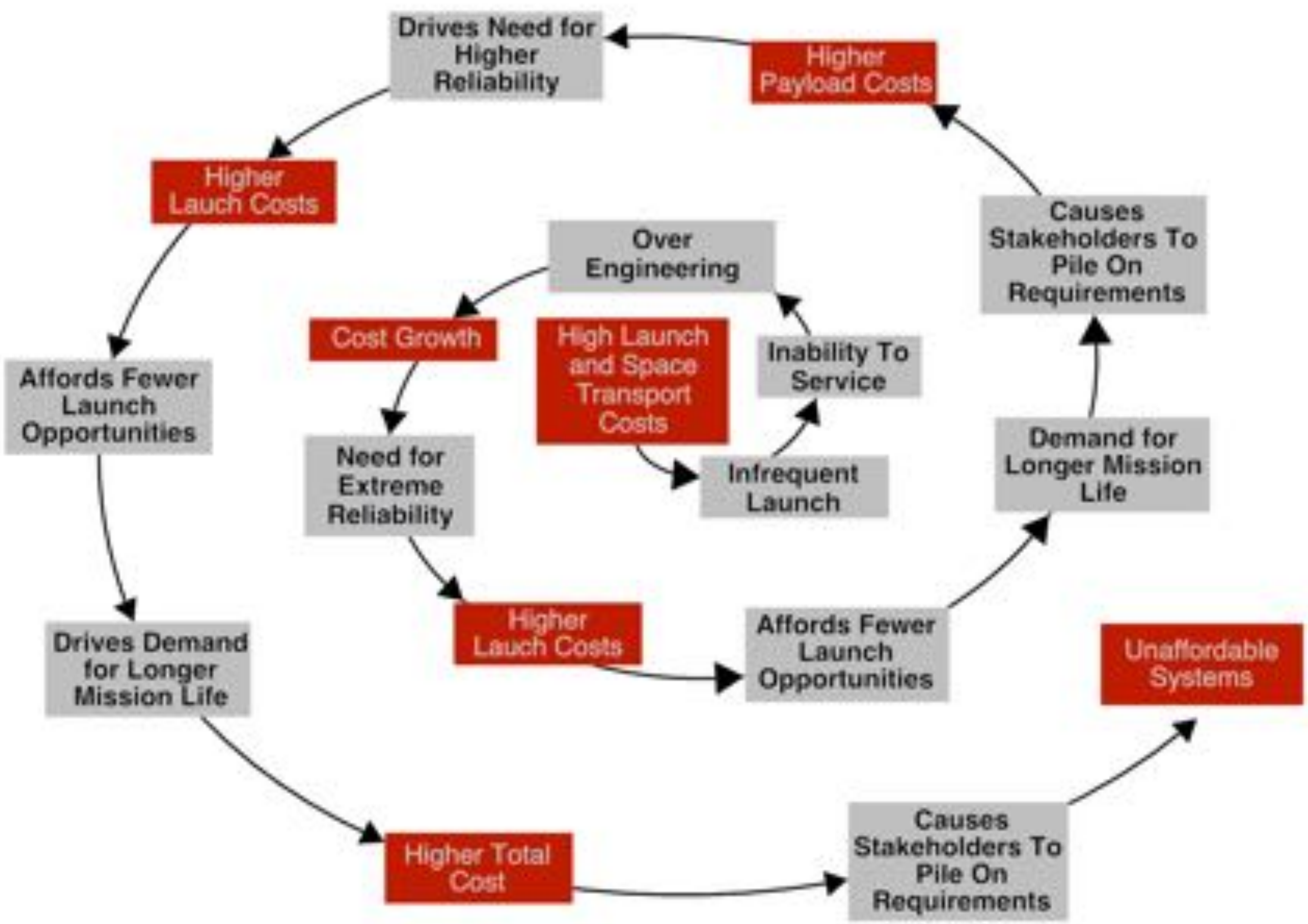
Not a Set of Answers

Today: Highlights of a Study of Broad Scope

# Coauthors

- Study Team
  - James R. French: Mission scenarios
  - Craig Peterson: Study systems engineering
  - Anthony Longman: Vehicle configurations and graphics
- Review Support
  - Stanley Love (Astronaut), Mission operations and human factors
  - Lynn Harper and Dan Raskey of NASA Ames
  - Dr. Robert Shishko of JPL
- Collaboration on Fontus system concept
  - Dr. Christopher Dreyer of Colorado School of Mines and colleagues

# Where We Are, Still Today



# Study Purpose

- The greatest impediment to NASA human exploration program is **cost.**
  - Cost is dominated by transportation costs, which is dominated by the cost of launching propellant.
- Goal is self-sustaining, reusable transportation with Apis™ (Asteroid Provided In-Situ Supplies) (Sercel 2016)
  - Apis™ architecture includes new approach to asteroid ISRU called "Optical Mining™" (Sercel 2015).

Assess the Economic Viability of Asteroid ISRU to Support NASA Human Exploration

# Why Now?

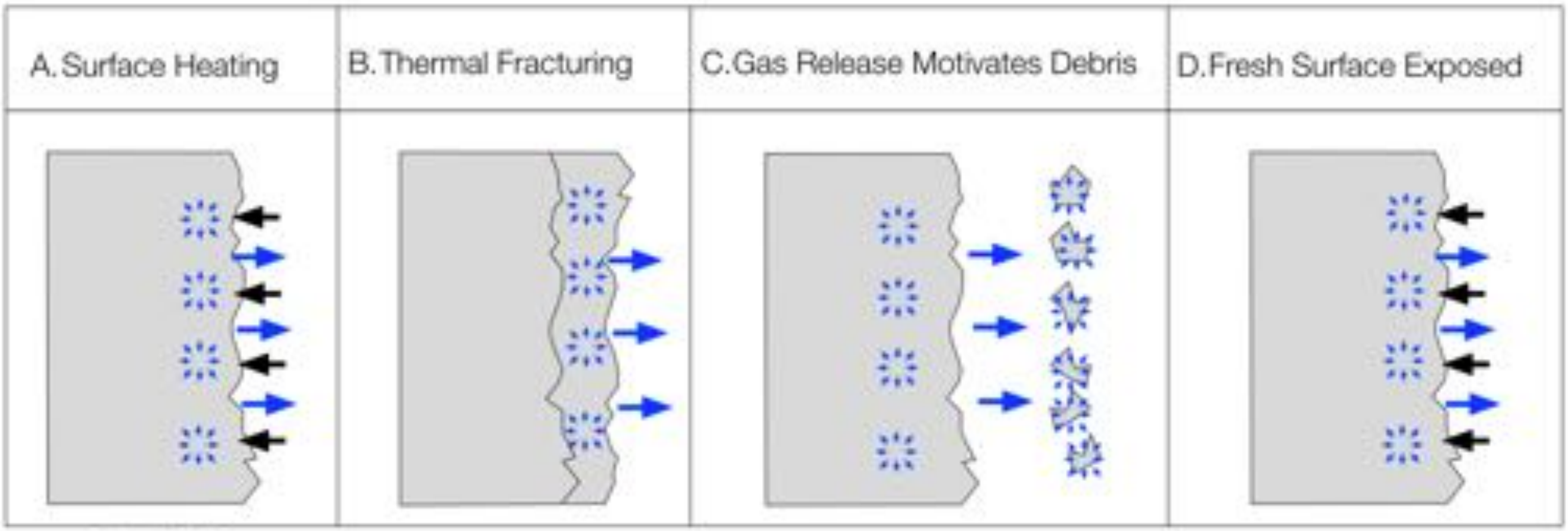
- The rise of the billionaire visionary
- Vindication of PPP through COTS etc.…
- Agile methods proven for aerospace (e.g. SpaceX)
- Understanding of the availability of space resources
  - Low ΔV water rich NEOs
  - Lunar ice close to the peaks of perpetual light

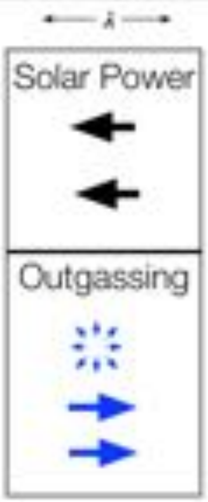
The Rush To Cislunar Space Started With Blue Origin's Proposal to NASA

# Mission Architecture

- Fully reusable launch vehicles
- Full reusable in-space vehicles
- No single-mission-type vehicles
  - e.g.: the same lander works on Mars and Moon
  - The lander is also a reusable 2nd stage system
- All in space propellant provided from ***above***
- Propellant depot at the <u>top</u> of the Earth-Moon gravity well
- Launch ***nothing*** beyond LEO or LMO
  - Payload or Propellant Transfer In low orbit from aerobraking tankers

# Thermal Spalling: Key to Optical Mining™




Progress continues at ≈1m/hr at surface blackbody peak temperature ≈1000K:

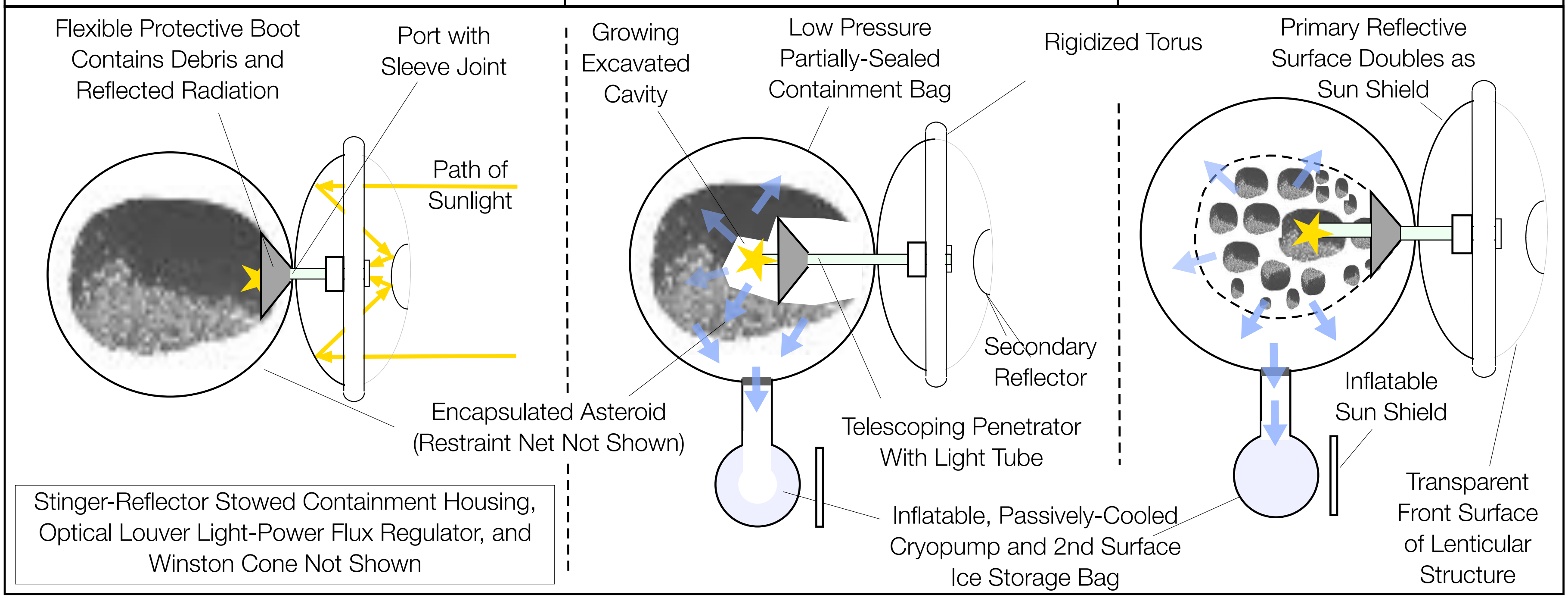
1. Cold surface temperature rises to near the blackbody temperature associated with the intensity of the applied radiation over a period of a few seconds establishing a mm scale hot layer.
2. A spall surface is created primarily by compressive thermal stress aided by thermal shear and gas pressure gradient.
3. mm scale spall particles fully outgas in seconds as surface outgassing drives them from the asteroid.
4. Process repeats in a continuous fashion exposing new surface to applied radiation.

# Optical Mining™

Fig. 1a: Optical Mining Starts With Asteroid Capture and Despin

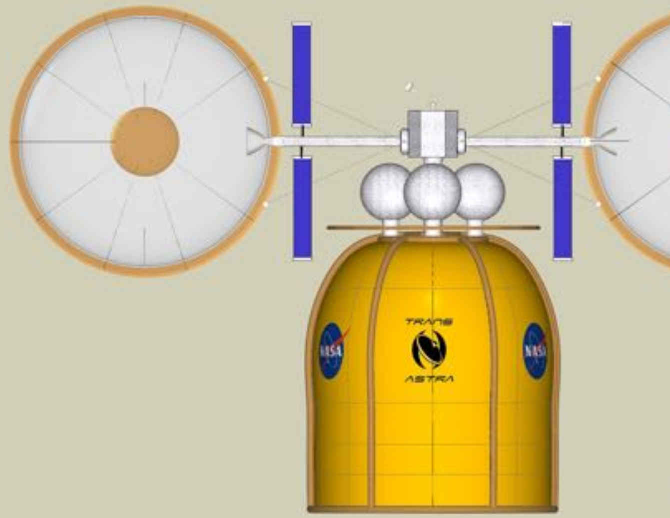
Fig. 1b: Excavation by Spalling and Outgassing

Fig. 1c: Volatile Products Stored as Ice



# Honey Bee Spacecraft Configuration

Honey Bee With Inflatable Bag in Asteroid Capture Configuration

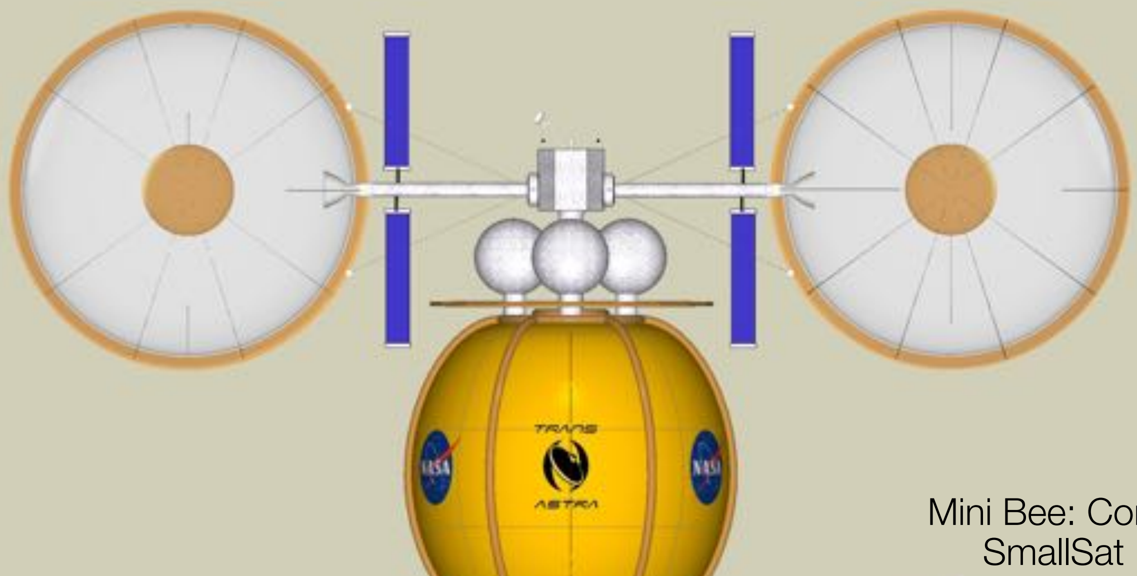


Design Adapted from Sercel Apis™ NIAC Study

4,000 kg Class Vehicle Requires Full Falcon 9 FT

Mini Bee: 250 kg Technology Demonstration Vehicle

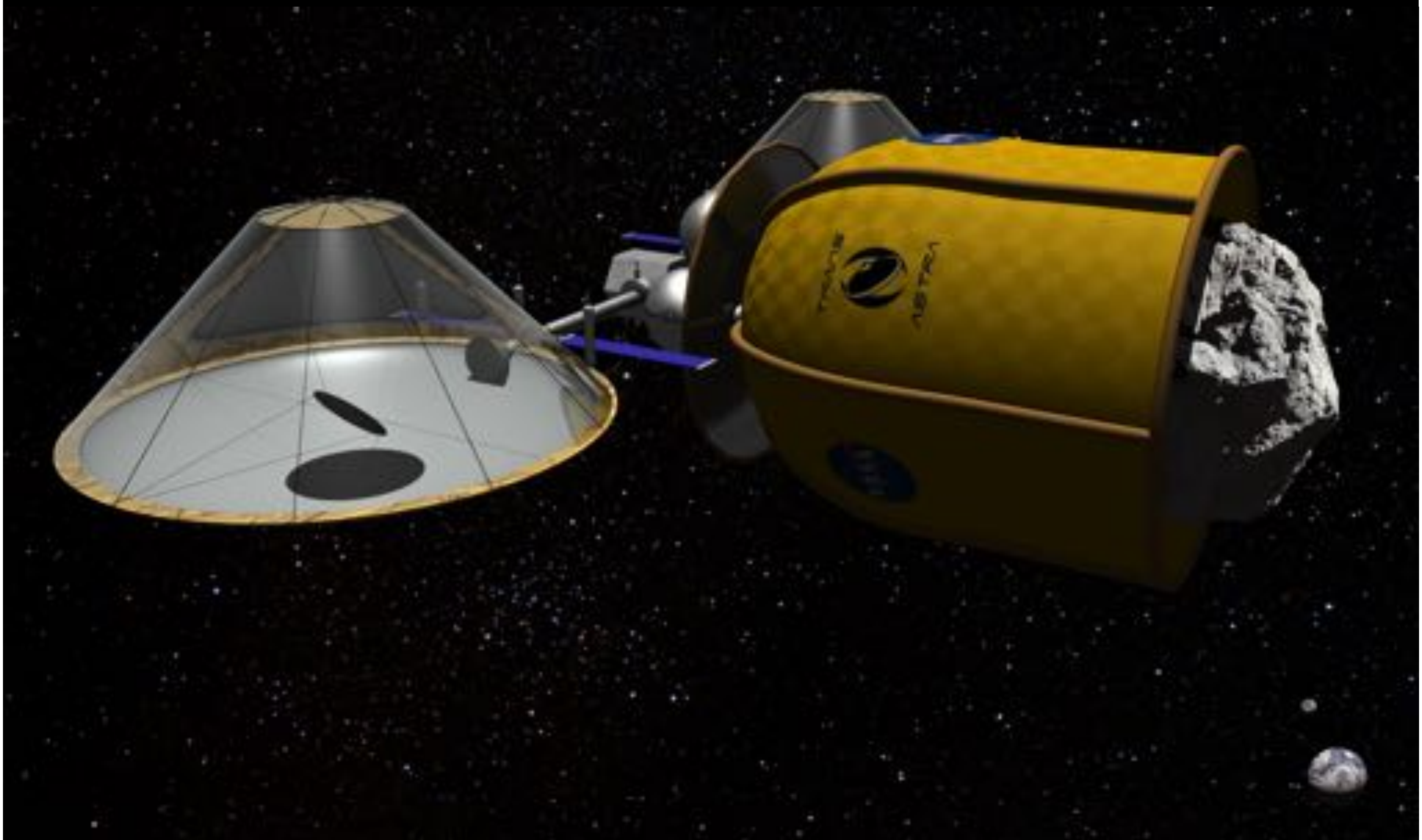
15 m Diameter Inflatable Reflector

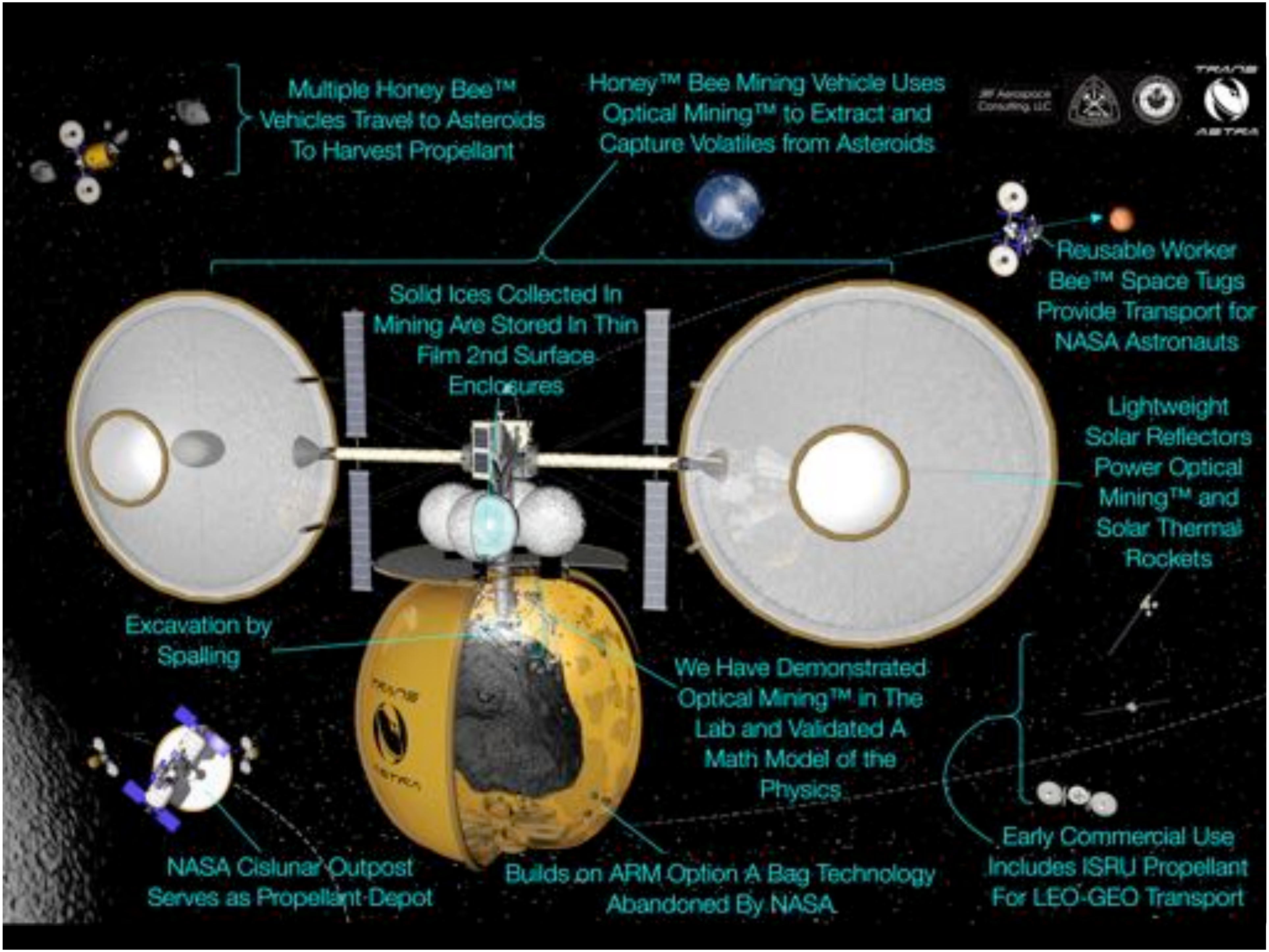


Honey Bee™ With Asteroid Captured in Containment Bag

Mini Bee: Compatible With SmallSat Launchers

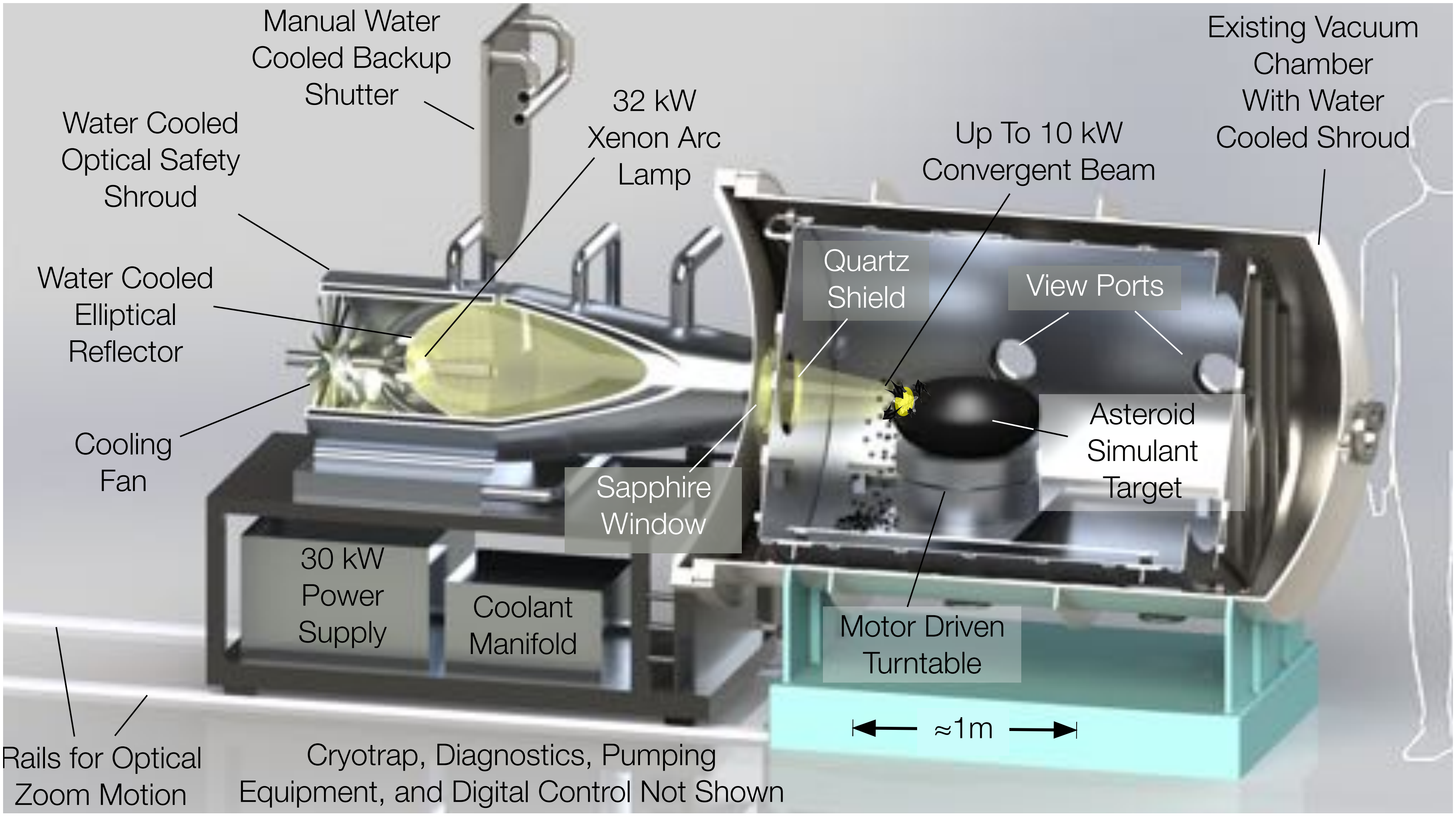
# Honey Bee Robotic Asteroid Capture for ISRU Resource Return




Multiple Honey Bee™ Vehicles Travel to Asteroids To Harvest Propellant
Honey™ Bee Mining Vehicle Uses Optical Mining™ to Extract and Capture Volatiles from Asteroids
Reusable Worker Bee™ Space Tugs Provide Transport for NASA Astronauts
Solid Ices Collected In Mining Are Stored In Thin Film 2nd Surface Enclosures
Lightweight Solar Reflectors Power Optical Mining™ and Solar Thermal Rockets
Excavation by Spalling
We Have Demonstrated Optical Mining™ in The Lab and Validated A Math Model of the Physics
NASA Cislunar Outpost Serves as Propellant Depot
Builds on ARM Option A Bag Technology Abandoned By NASA
Early Commercial Use Includes ISRU Propellant For LEO-GEO Transport

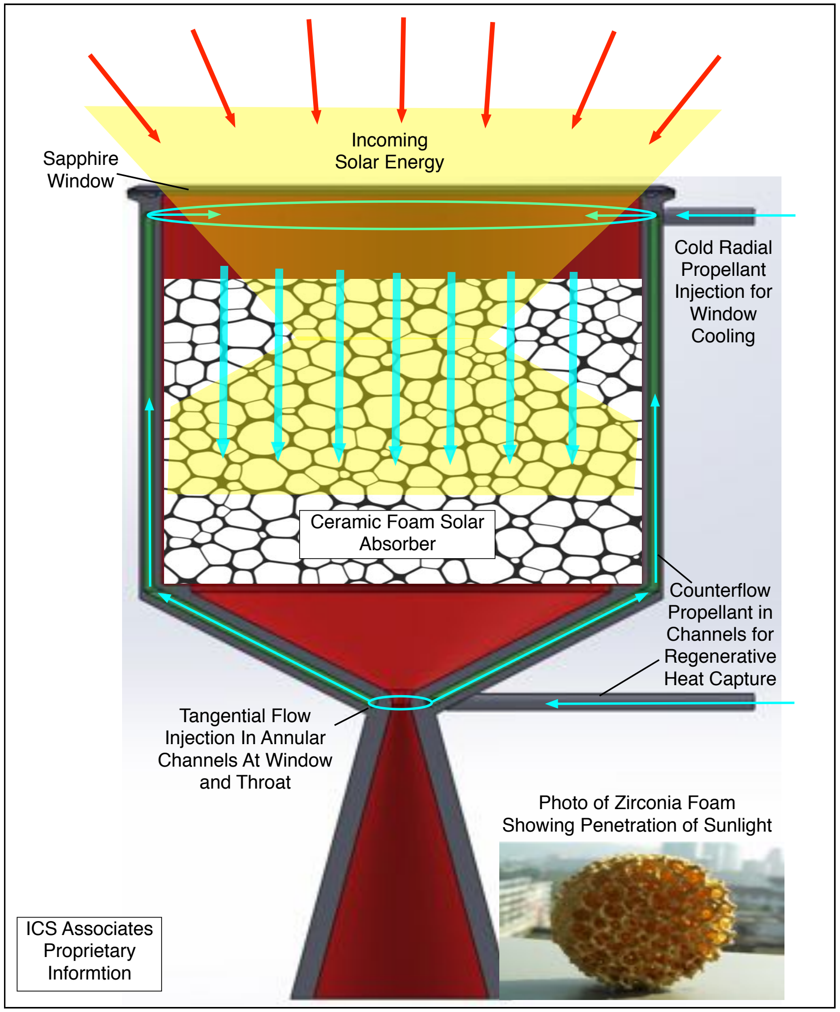
# But First

# The Next Step…
# The Optical Mining™ Test Bed (OMTB)



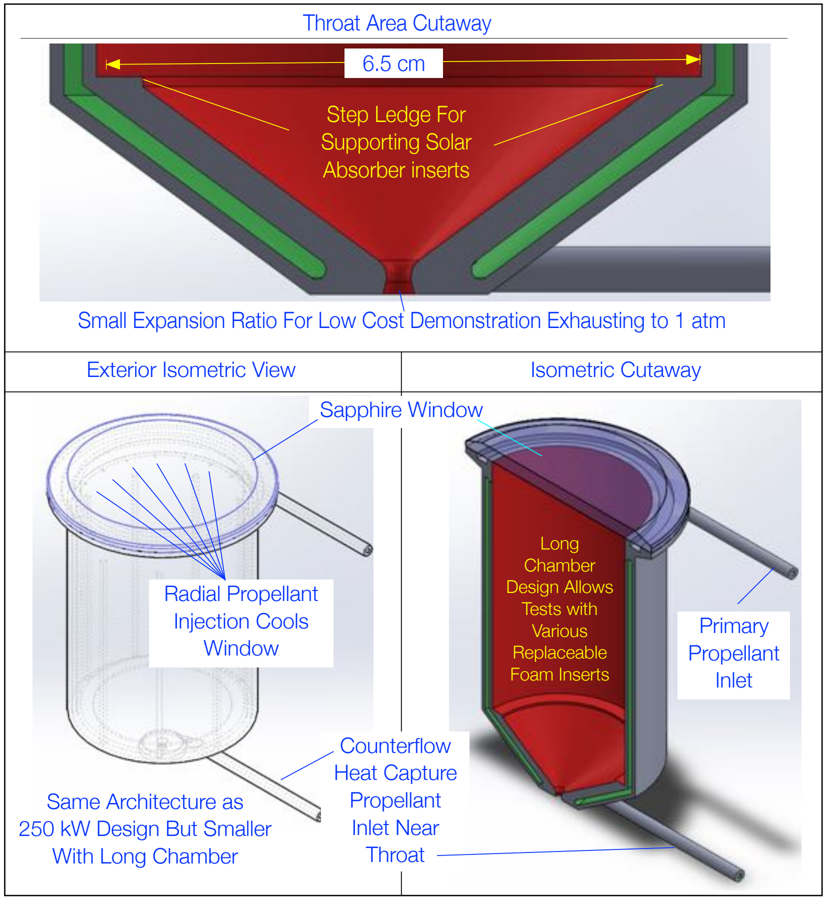

**Builds on Complete Theory and Dozens of Demonstrations**

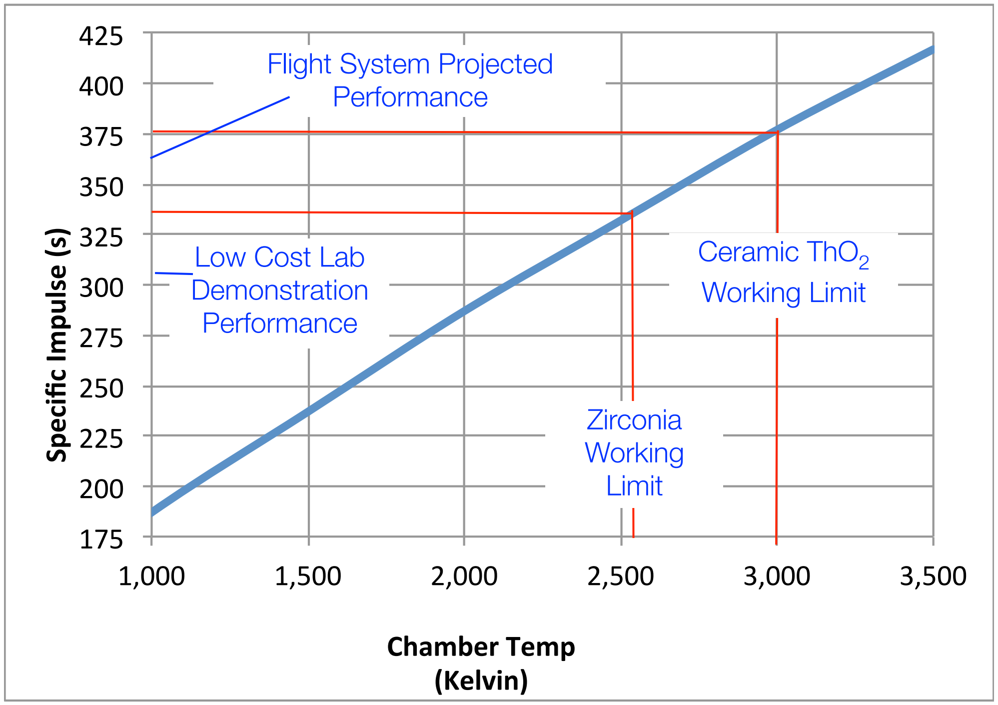
# High Performance Solar Thermal Propulsion




Thorium Oxide For Flight Systems

# High Performance Solar Thermal Propulsion




NIAC Phase II Proposal Pending

# Mission Scenarios Studied

- Lunar Orbital Outpost
  - Established in Lunar Distant Retrograde Orbit (LDRO) and operated for life of scenario
- Human Near Earth Object (NEO) Exploration
  - Focused on crewed missions to a variety of small (10 m class) targets (five 14 month missions)
- Lunar Surface Operations (LSO)
  - Establishment and operate a lunar surface base (two crewed and two cargo lander per year)
- Mars Exploration
  - Four crewed exploration mission to Deimos crewed Mars landing
  - Return missions could lead to establishment of Deimos or surface base, but not covered in the version of this scenario presented

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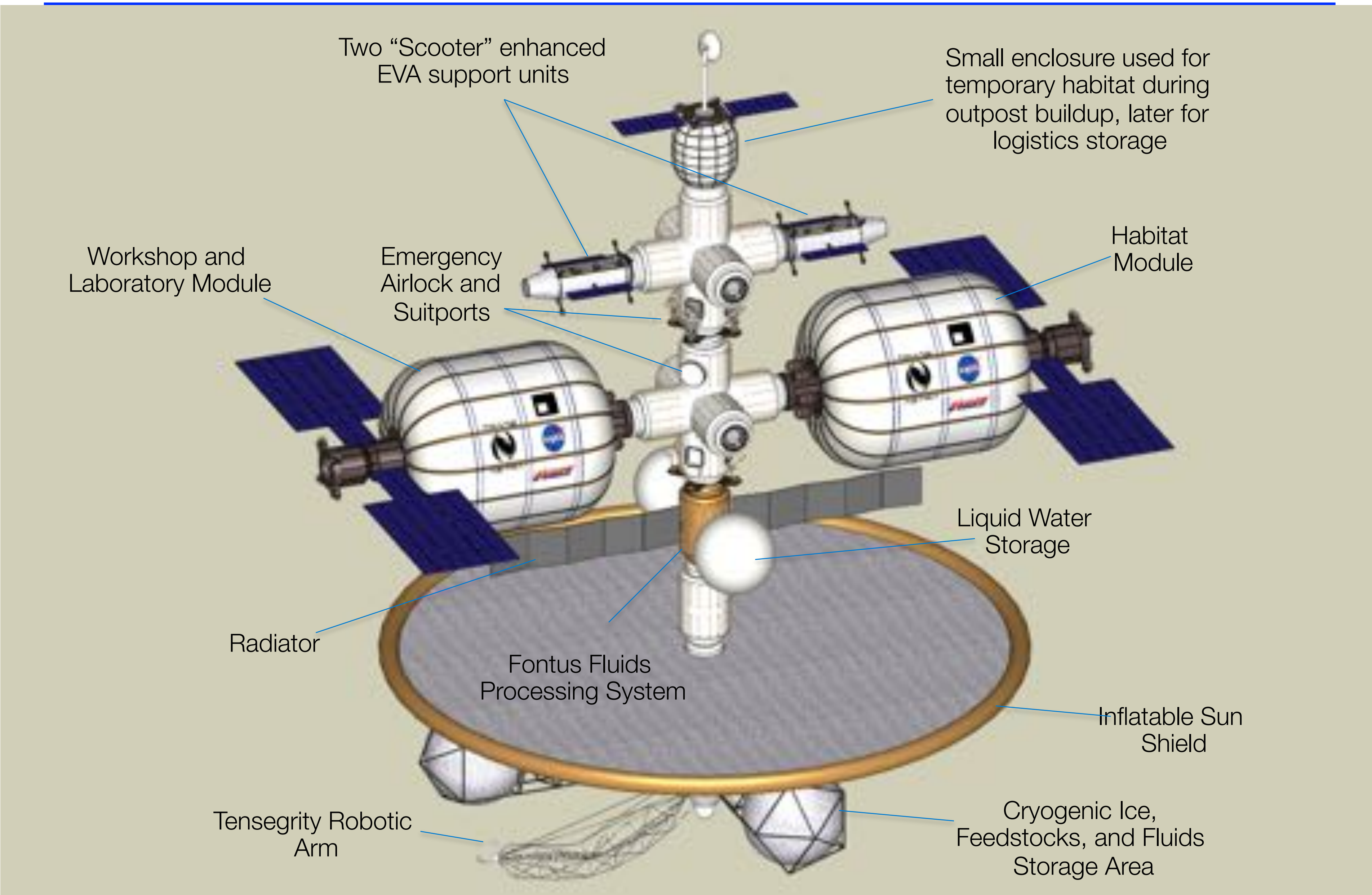
- LEO to GEO commercial satellite transportation
- Cislunar Tourism

# Combined Mission Schedule

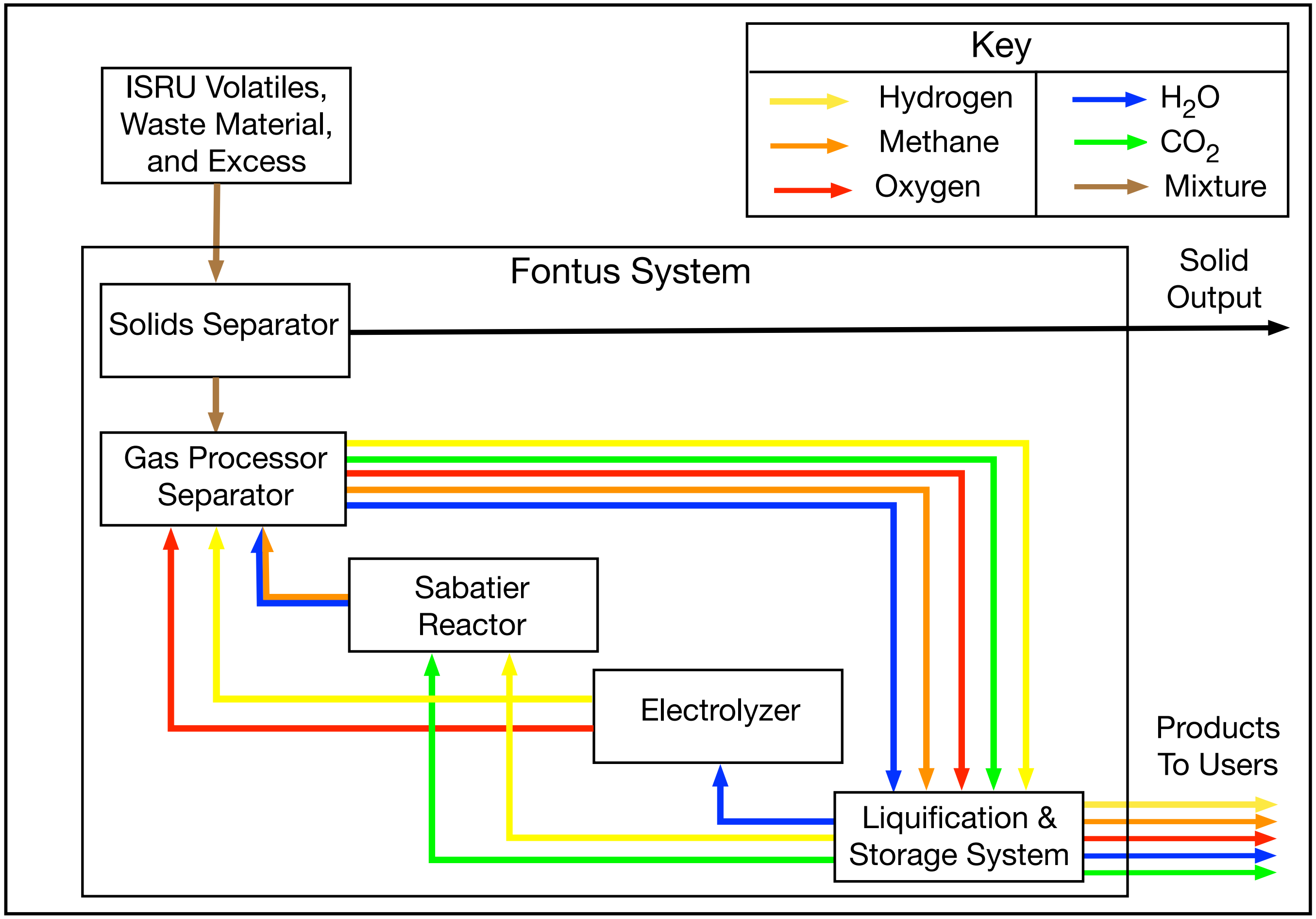
| | Start Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mission/Event | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 | 21 |
| Lunar Orbital Outpost | | | | | | | | | | | |
| Establishment | | | | | | | | | | | |
| Operations | | | | | | | | | | | |
| NEO Exploration | | | | | | | | | | | |
| Mission 1 (14 mo. Duration) | | | | | | | | | | | |
| Mission 2 | | | | | | | | | | | |
| Mission 3 | | | | | | | | | | | |
| Mission 4 | | | | | | | | | | | |
| Mission 5 | | | | | | | | | | | |
| Lunar Surface Operations | | | | | | | | | | | |
| Site Selection and Initial Base | | | | | | | | | | | |
| Base Expansion and Occupation | | | | | | | | | | | |
| Mars Exploration | | | | | | | | | | | |
| Mission 1 (30 mo. Duration) | | | | | | | | | | | |
| Mission 2 | | | | | | | | | | | |
| Mission 3 | | | | | | | | | | | |

- Mars and some NEO missions staged out of LEO in Non-ISRU case.
- All other missions staged out of LDRO from Honey Bee™ supplies.
  - Reusable Spaceship (all LOX-LM) picks up payloads in LEO and delivers them to LDRO Outpost in Apis™ cases

# Propellant Depot and Outpost Configuration

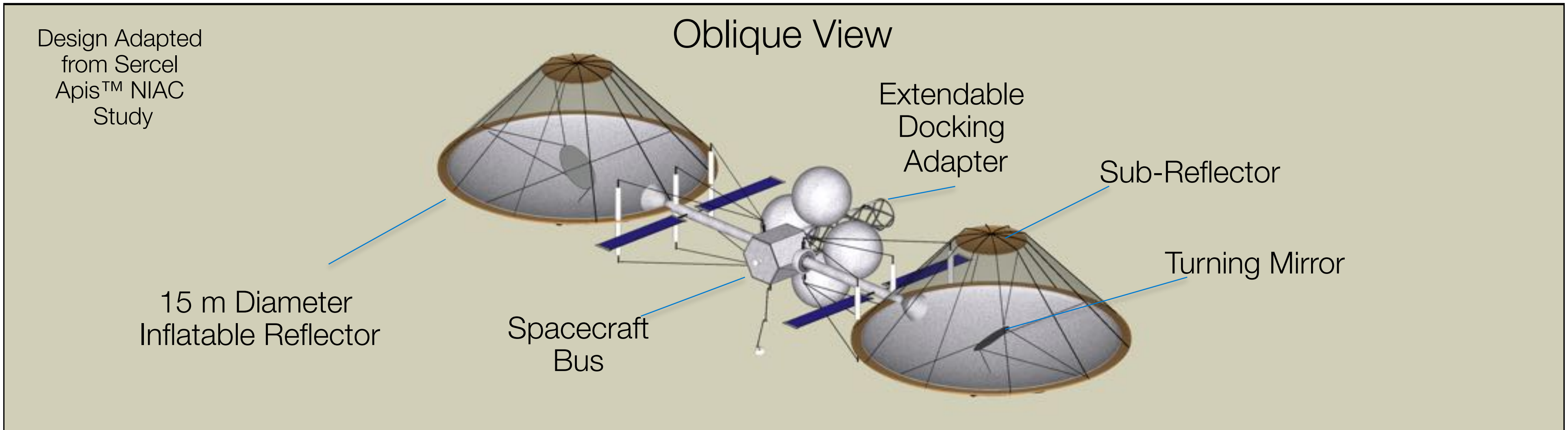


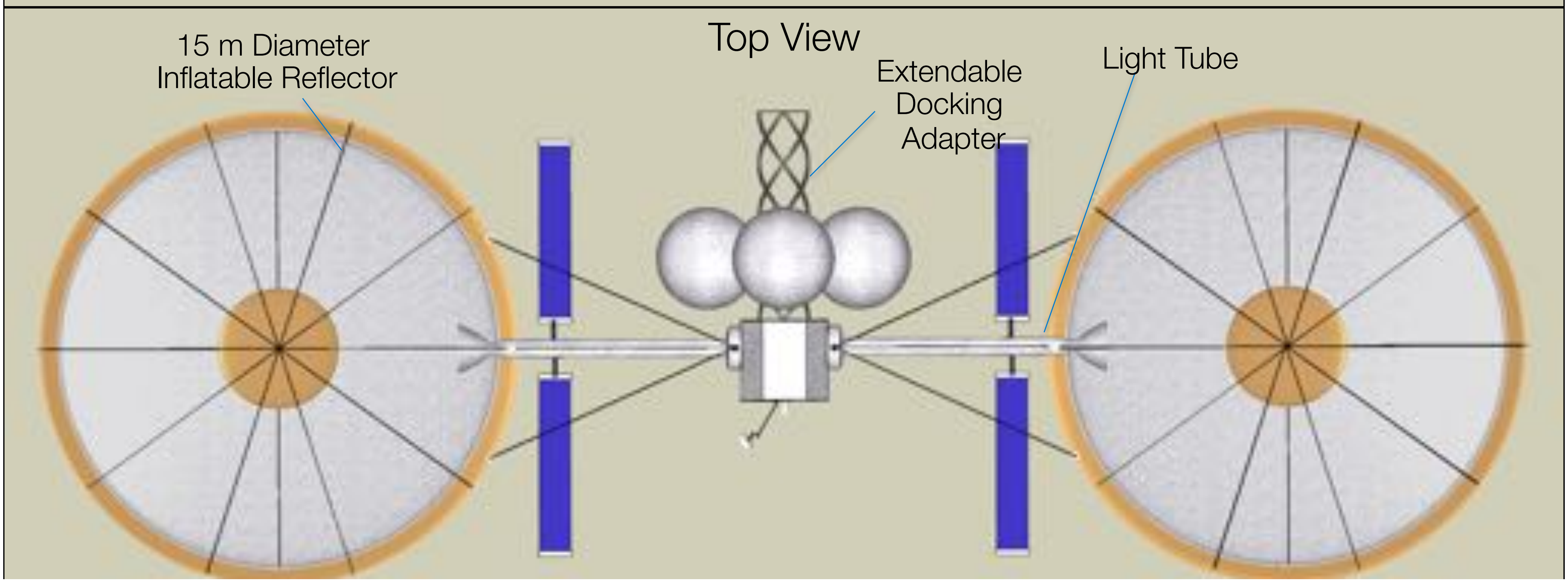
# Fontus Propellant Processing System Internal Material Flow



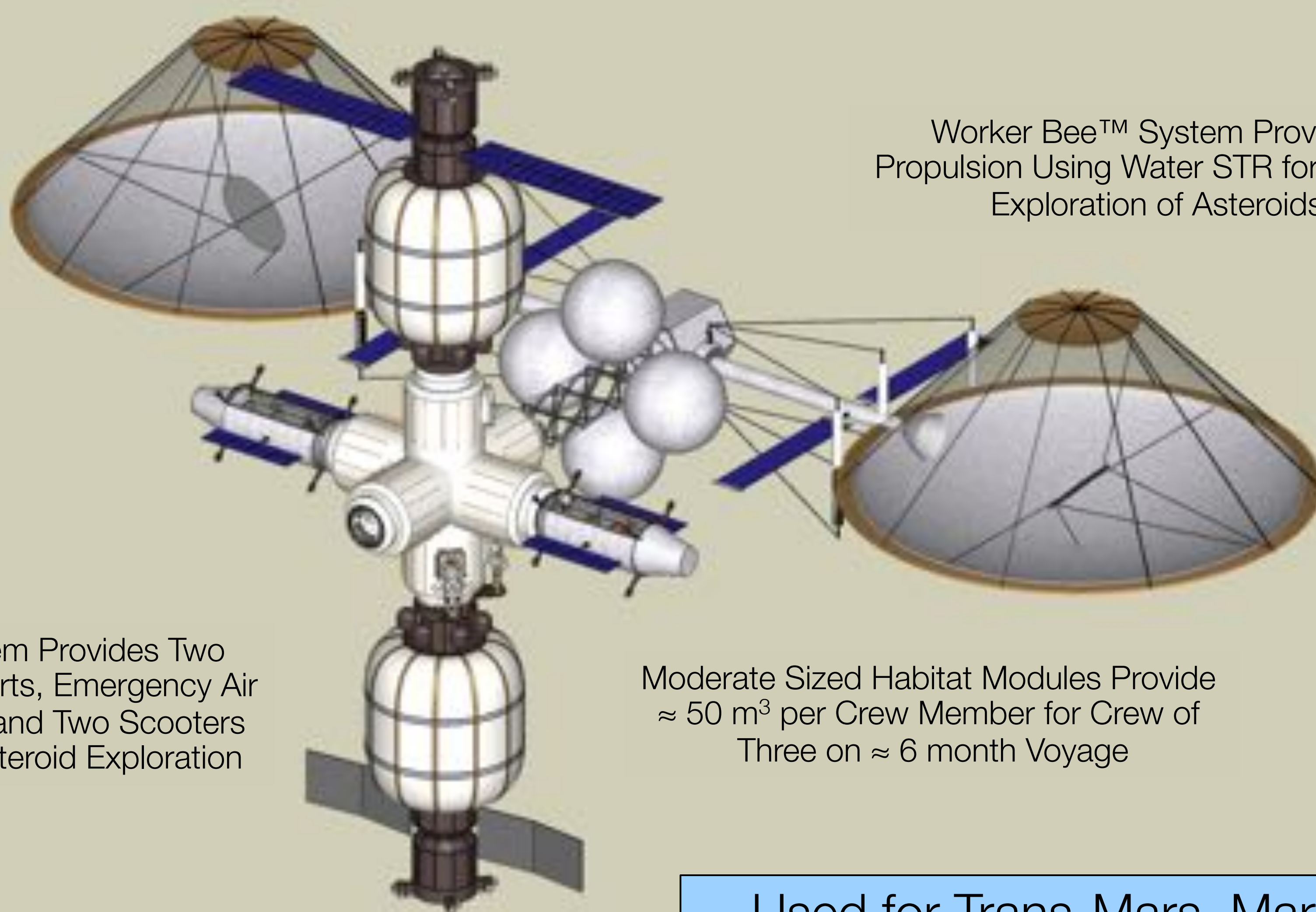

Fontus System extracts, separates, produces, and uses multiple materials prior to liquefaction and storage of the finished products

# Worker Bee™ Spacecraft Configuration



# Deep Space Exploration System (DSES)



Worker Bee™ System Provides Propulsion Using Water STR for Human Exploration of Asteroids

System Provides Two Suit Ports, Emergency Air Lock, and Two Scooters for Asteroid Exploration

Moderate Sized Habitat Modules Provide ≈ 50 $m^3$ per Crew Member for Crew of Three on ≈ 6 month Voyage

Used for Trans-Mars, Martian Moon, and Asteroid Exploration

# Honey Bee Spacecraft Configuration

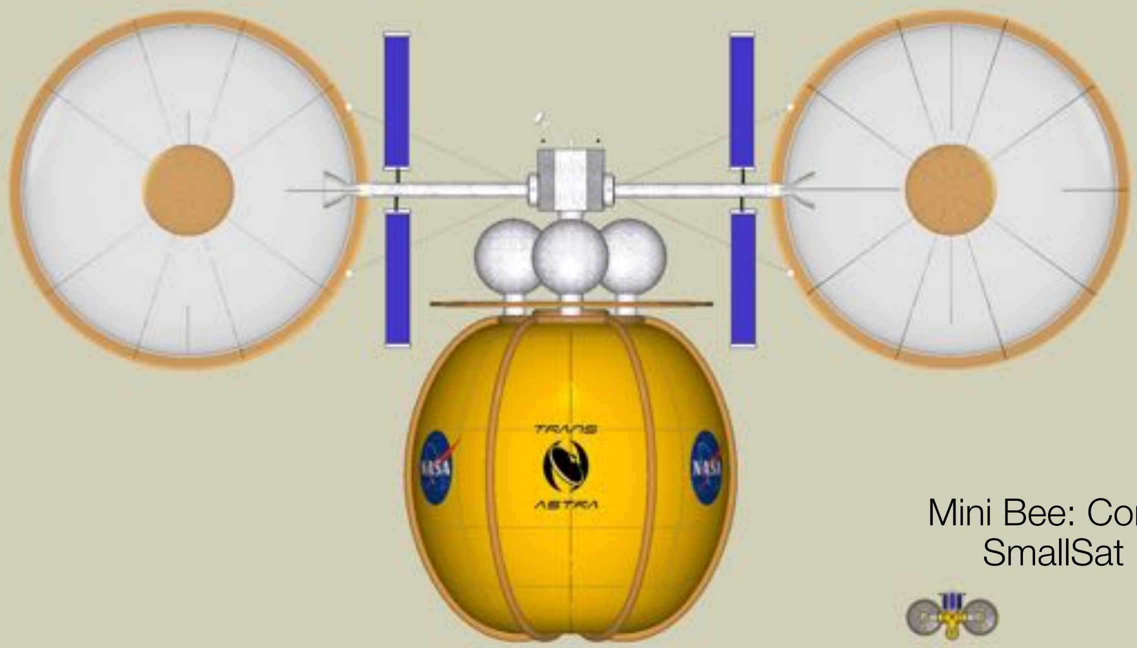
Honey Bee With Inflatable Bag in Asteroid Capture Configuration

Design Adapted from Sercel Apis™ NIAC Study

4,000 kg Class Vehicle Requires Full Falcon 9 FT

Mini Bee: 250 kg Technology Demonstration Vehicle

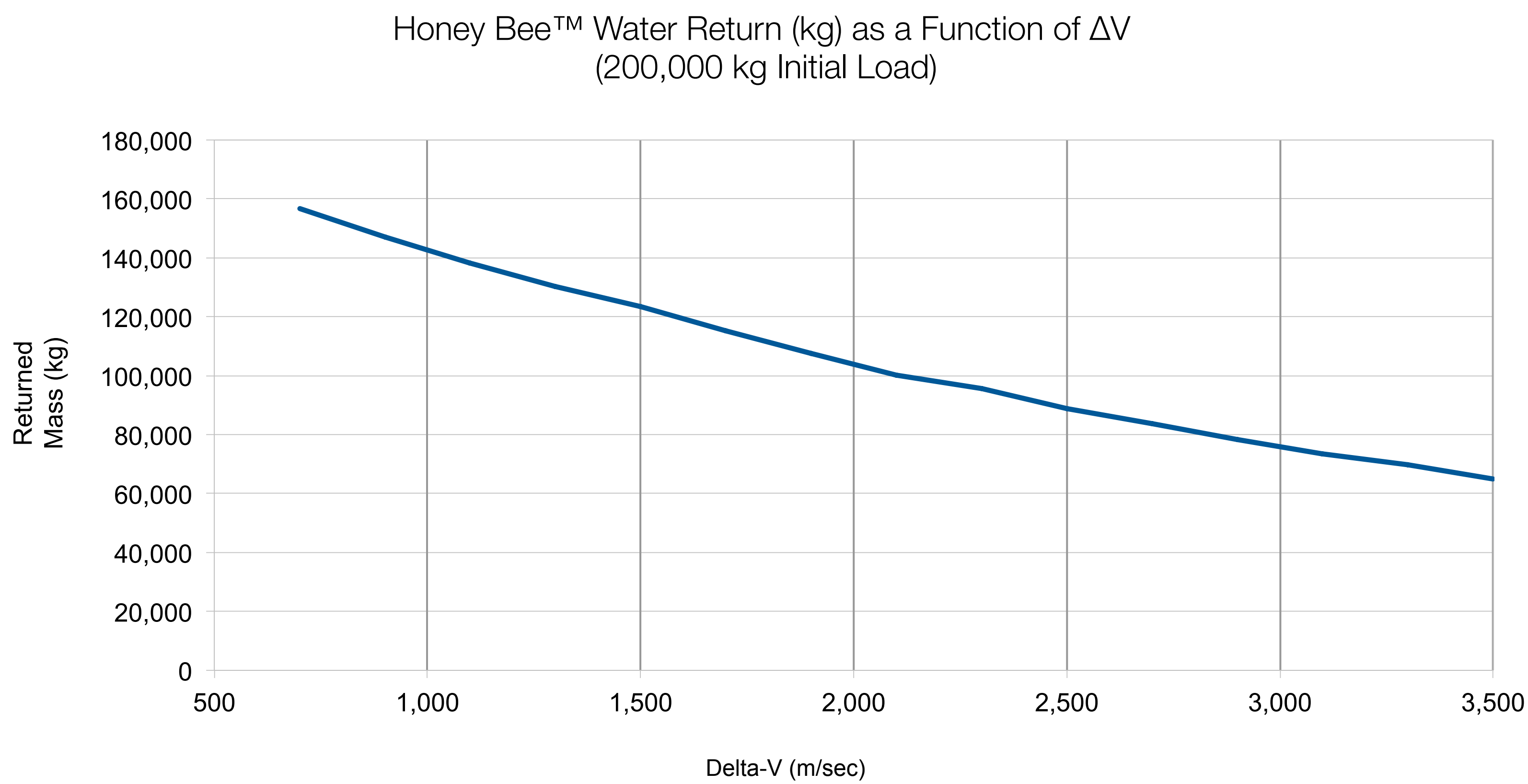
15 m Diameter Inflatable Reflector



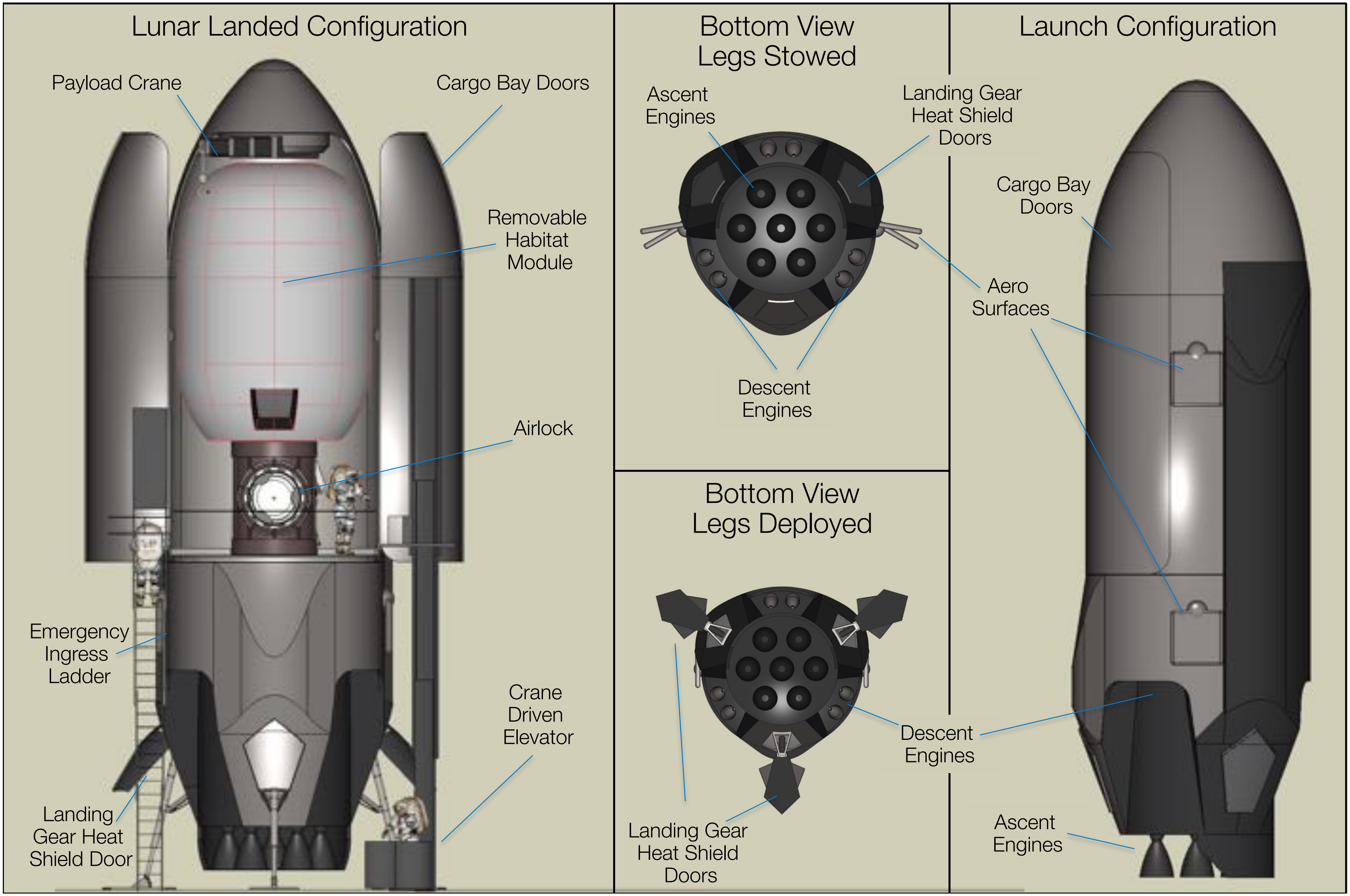
Honey Bee™ With Asteroid Captured in Containment Bag

Mini Bee: Compatible With SmallSat Launchers

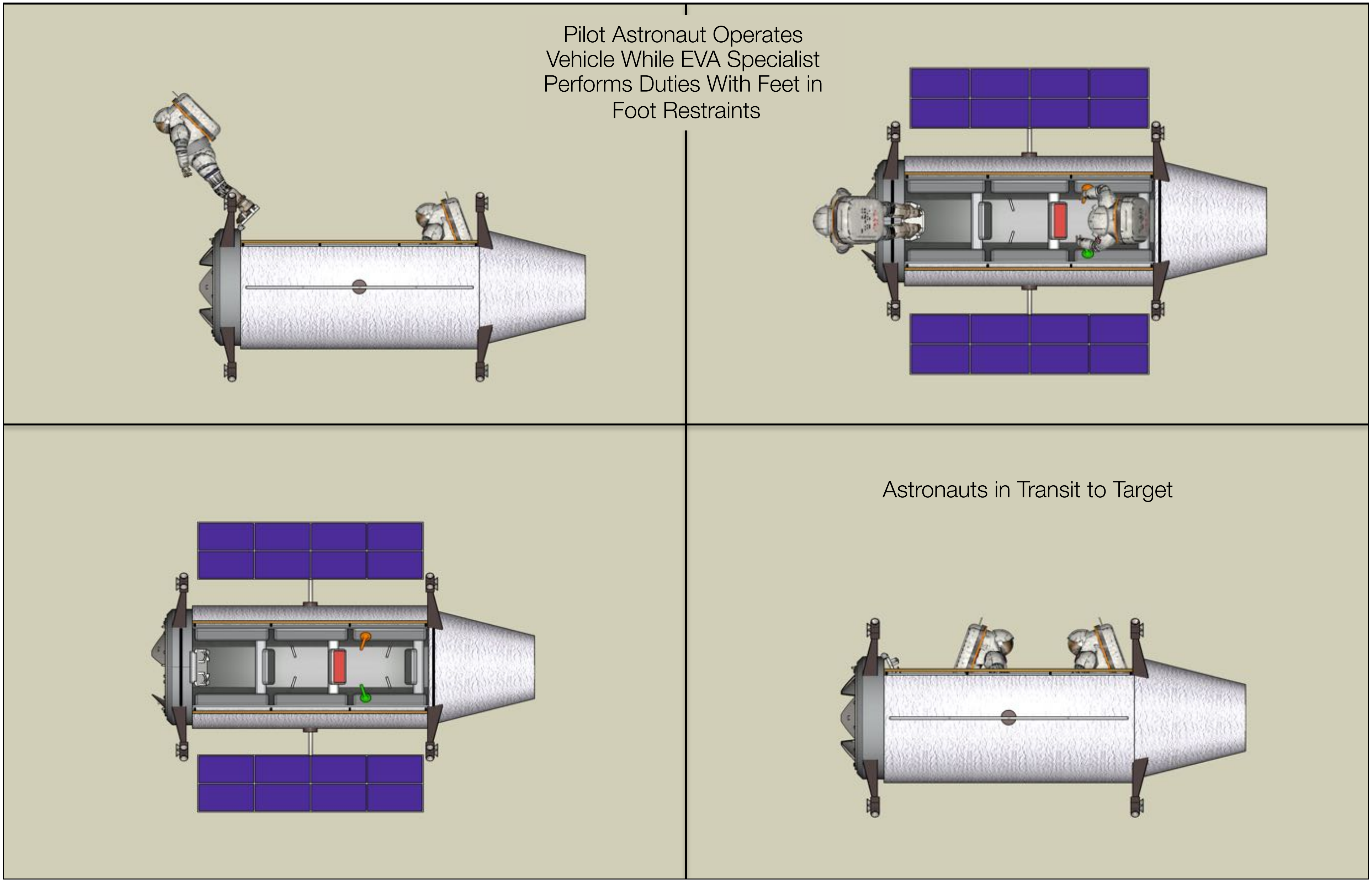
# Honey Bee for Asteroid Ice Return



# Reusable Spaceship Upper Stage

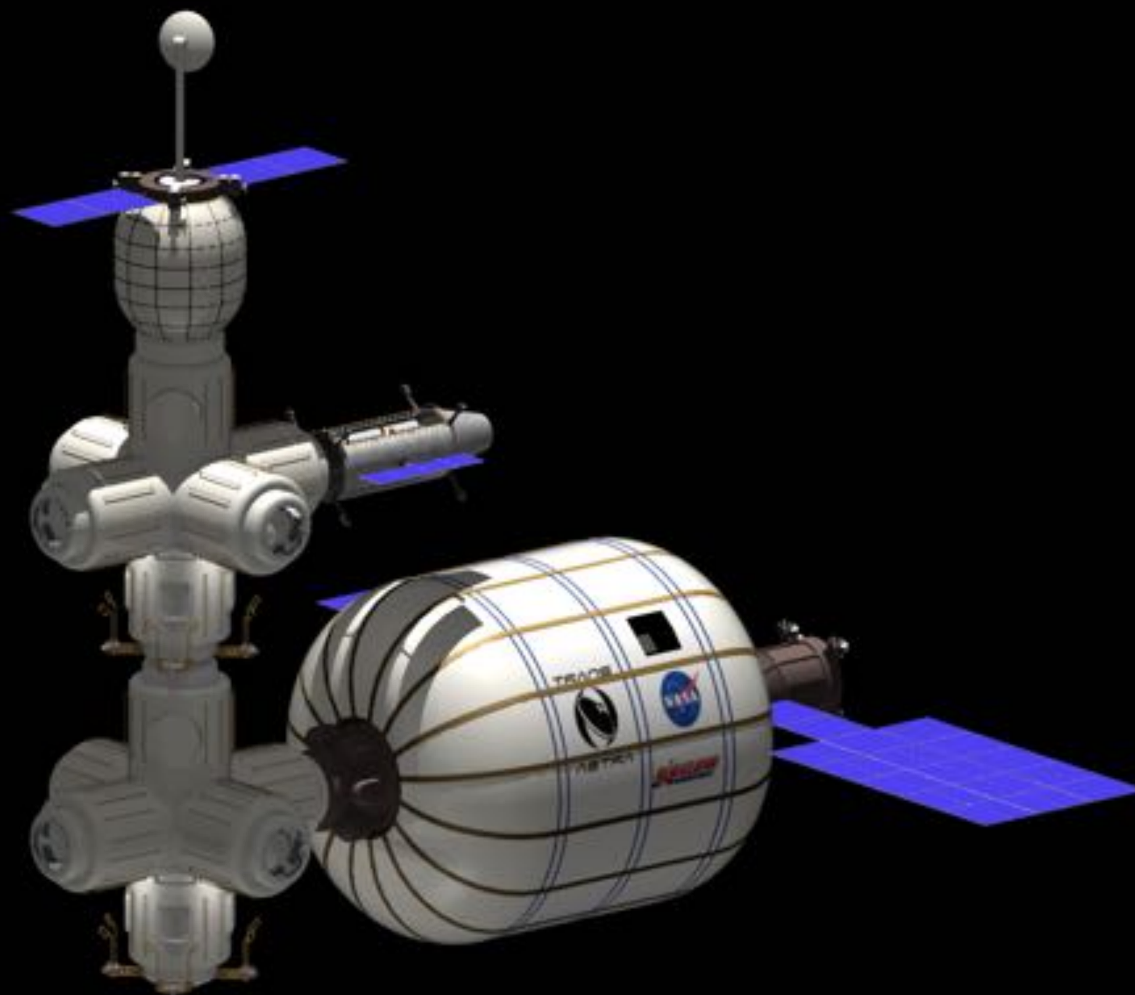


# Scooter Enhanced EVA Support System

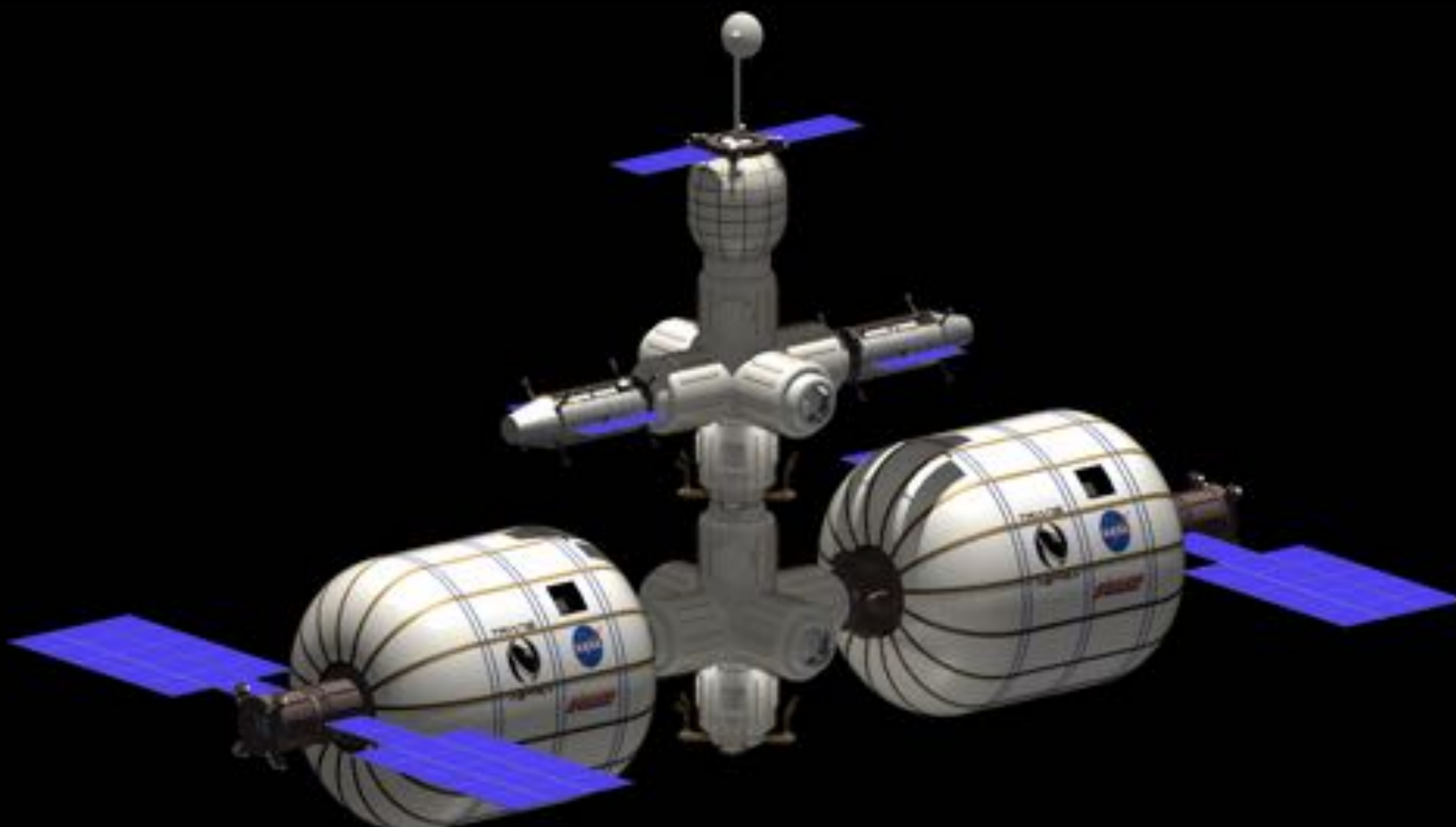


# Lunar Orbital Outpost Build Sequence (1)

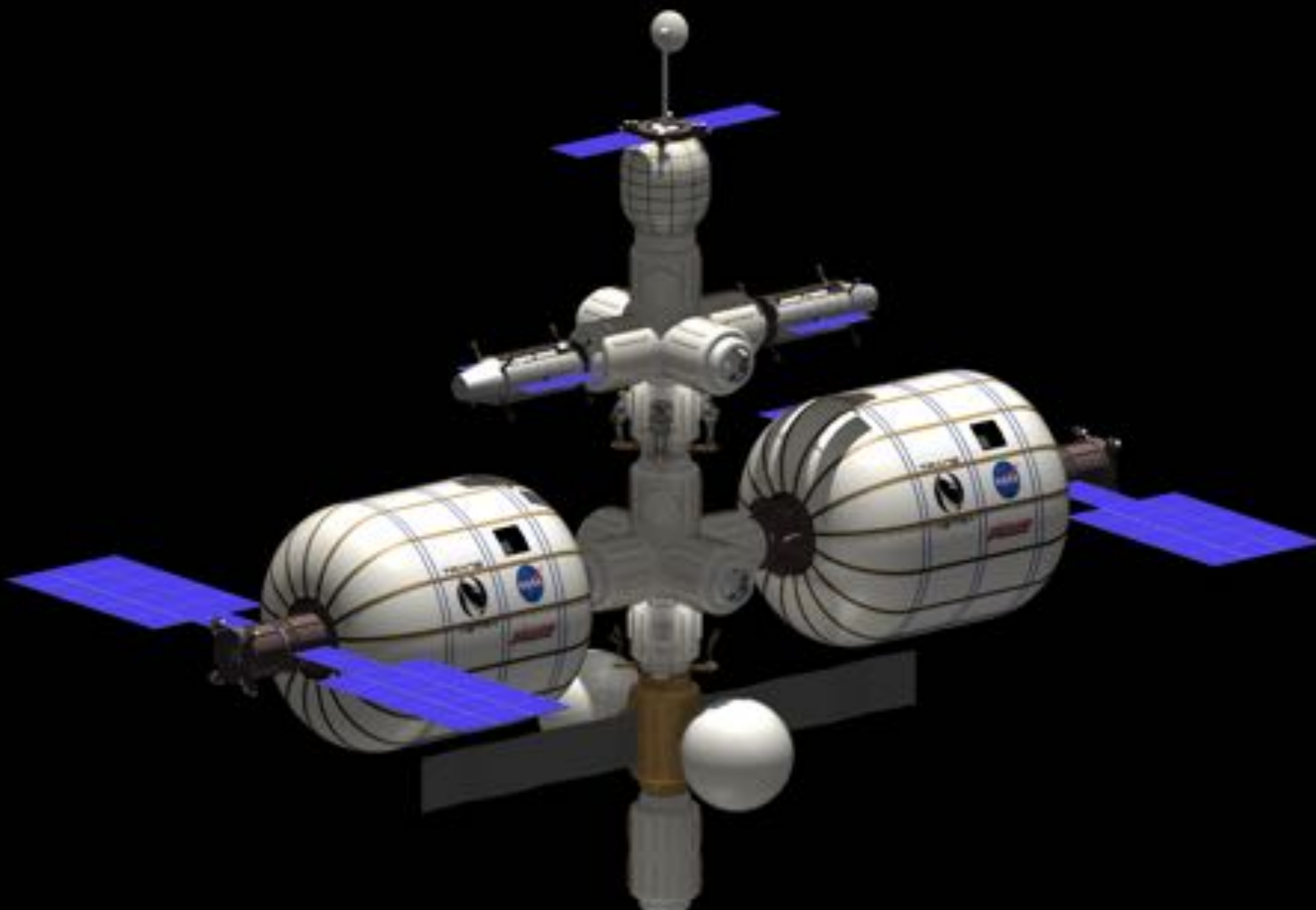
# Lunar Orbital Outpost Build Sequence (2)



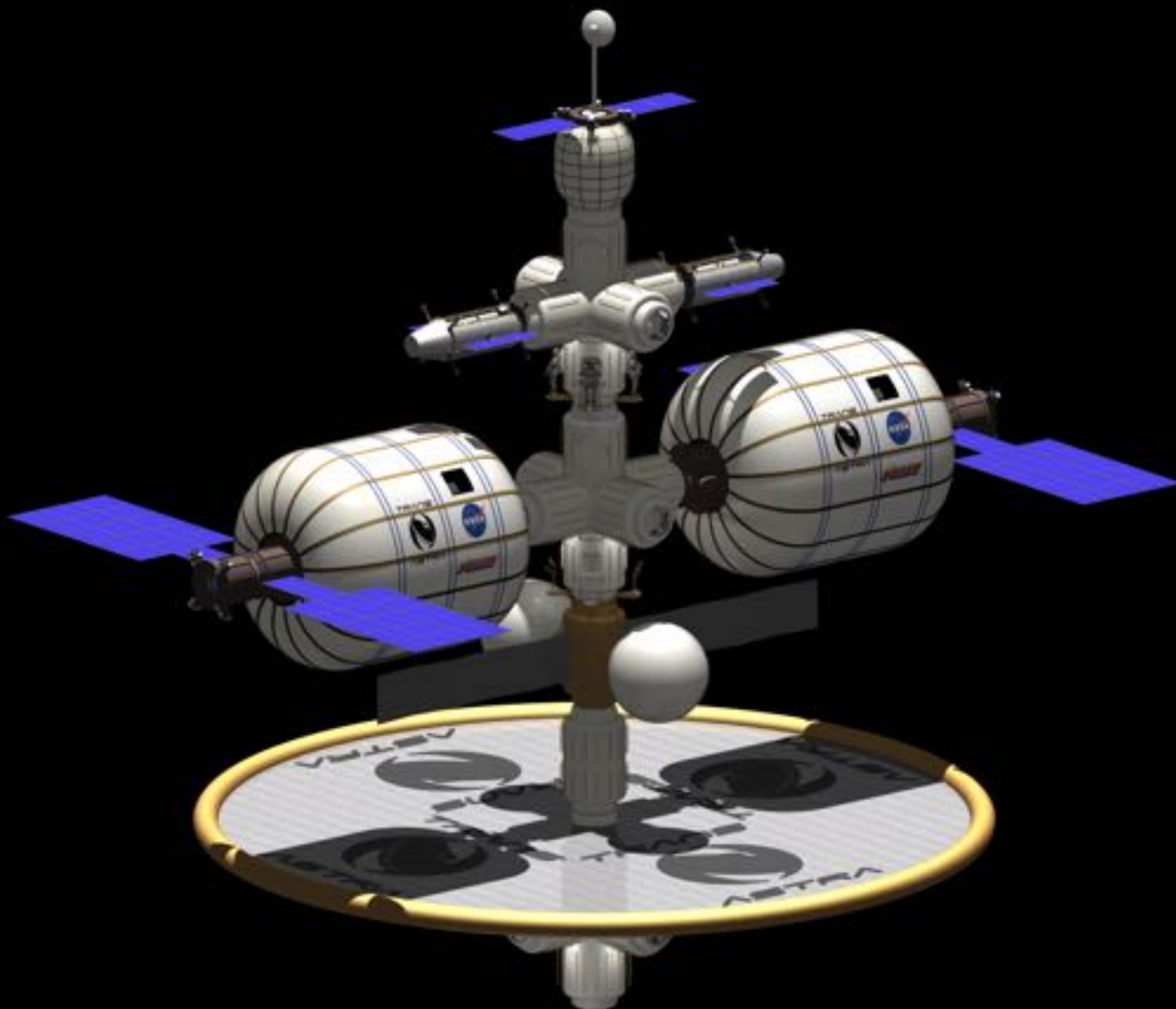
# Lunar Orbital Outpost Build Sequence (3)



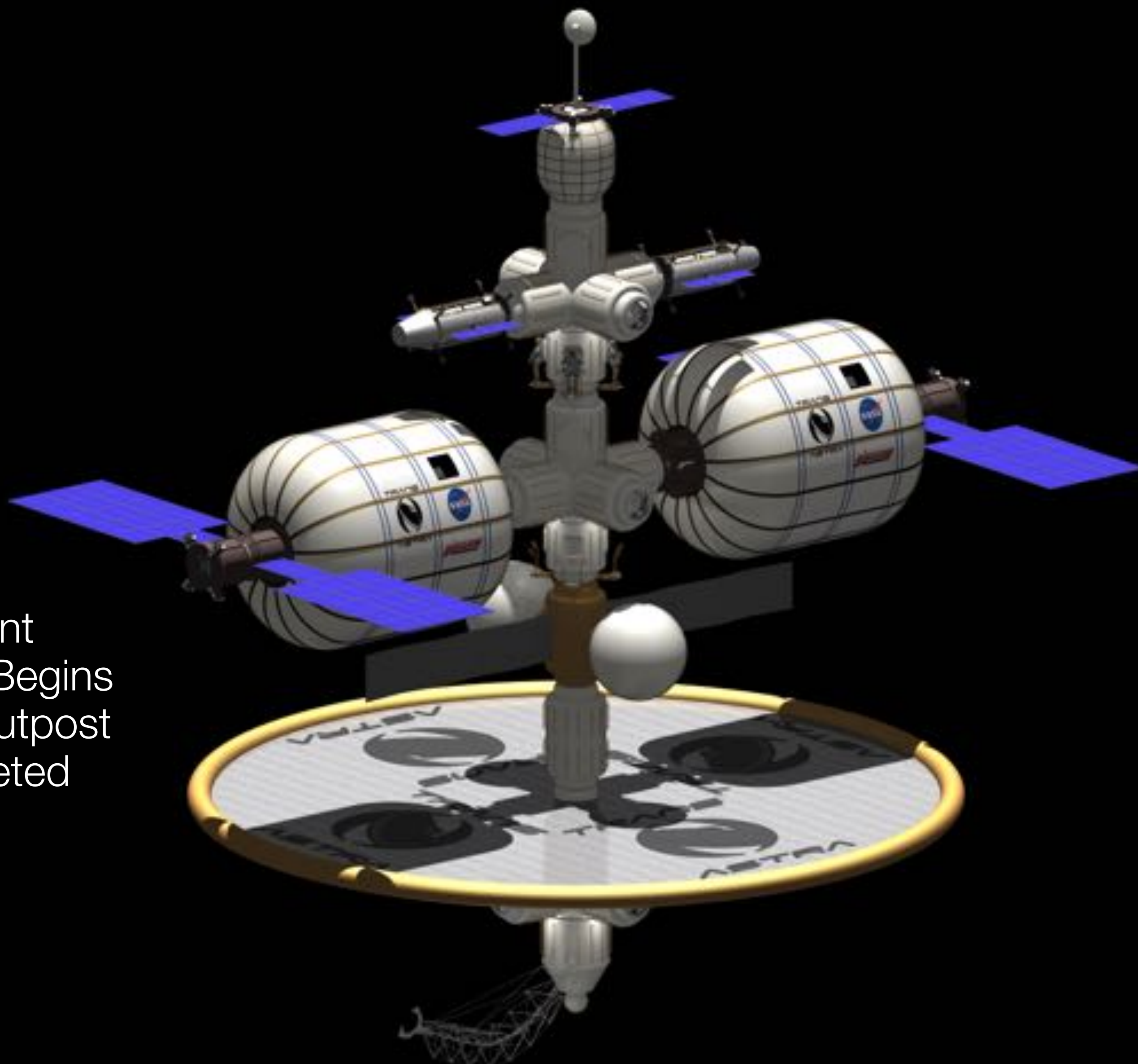
# Lunar Orbital Outpost Build Sequence (4)



# Lunar Orbital Outpost Build Sequence (5)

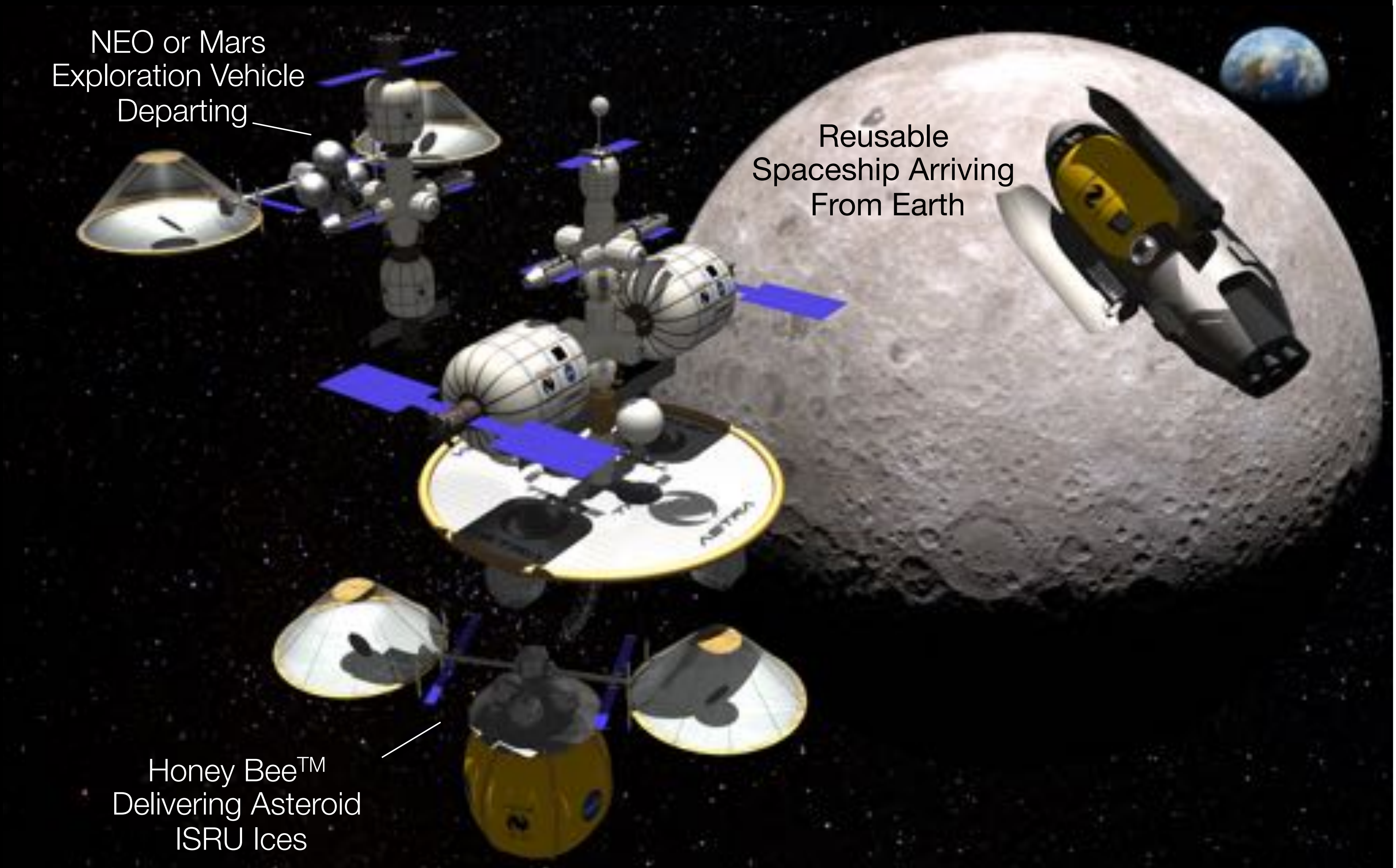


# Lunar Orbital Outpost Build Sequence (6)



Propellant
Processing Begins
When the Outpost
is Completed

# Operational Lunar Orbital Outpost



# NEO DSES Human Exploration Vehicle Configuration With Worker Bee™

Used for Both Human NEO and Mars Orbital Exploration (Forms the basis of an orbital outpost at Mars near Deimos orbit).

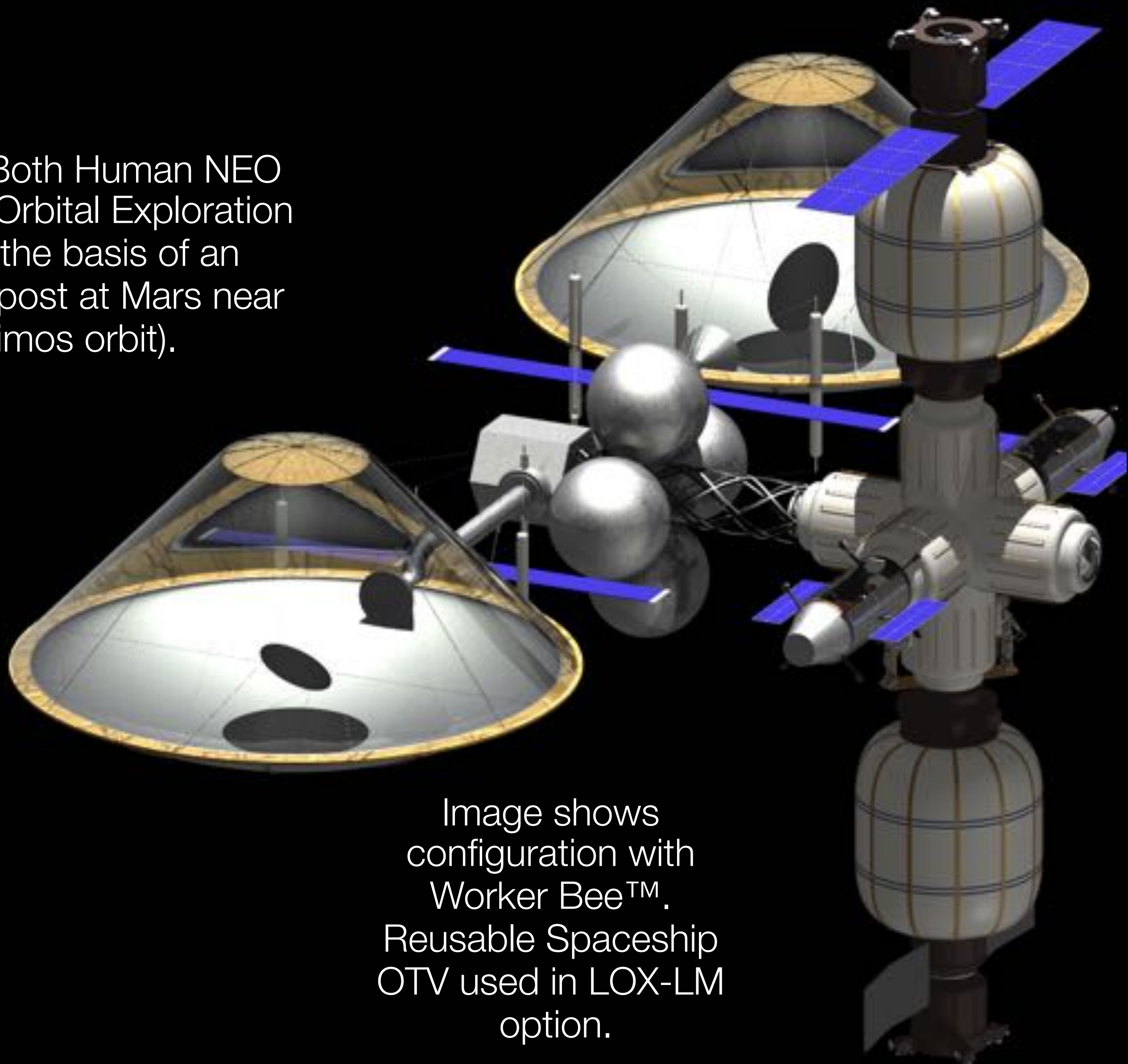
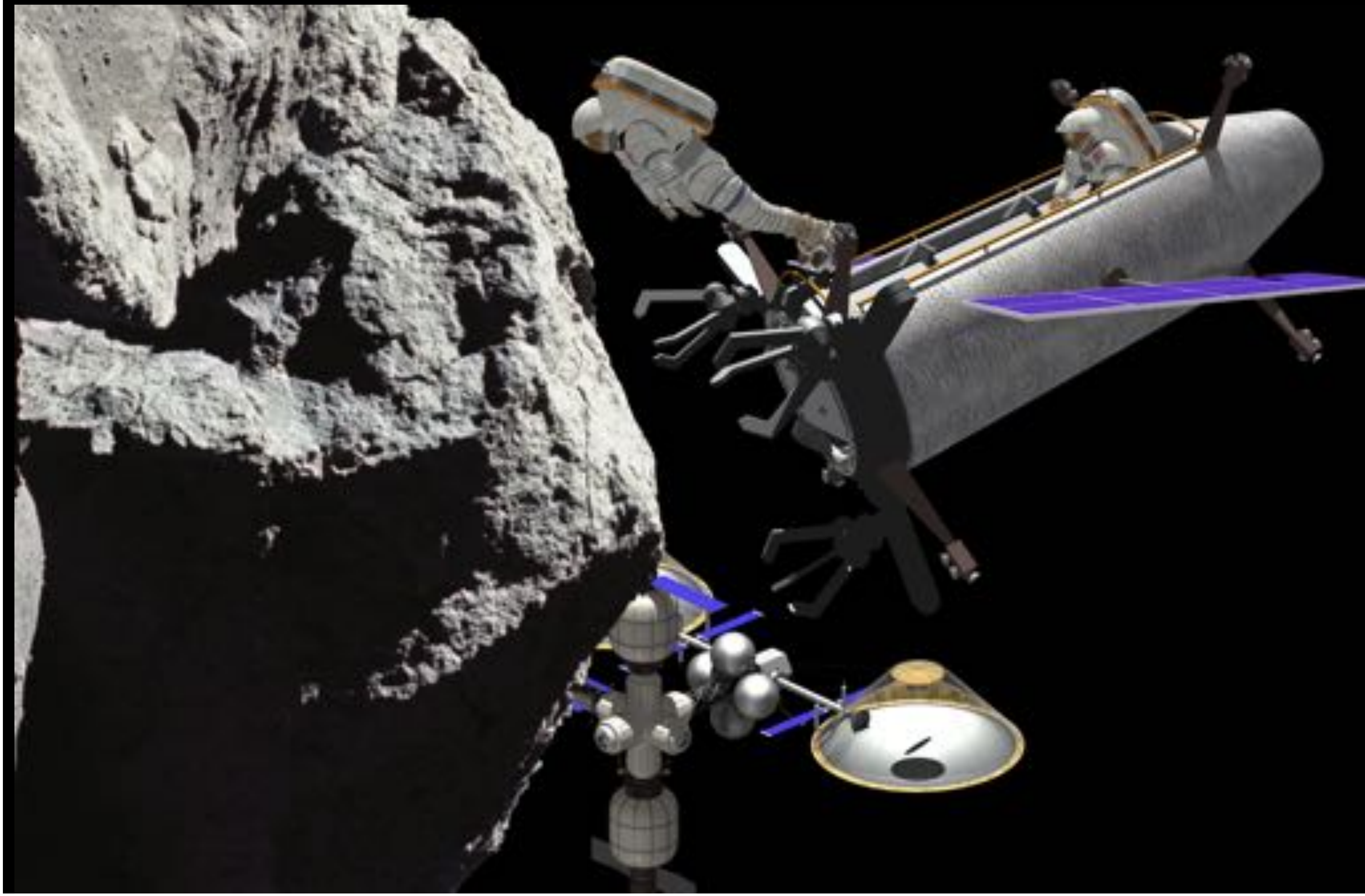
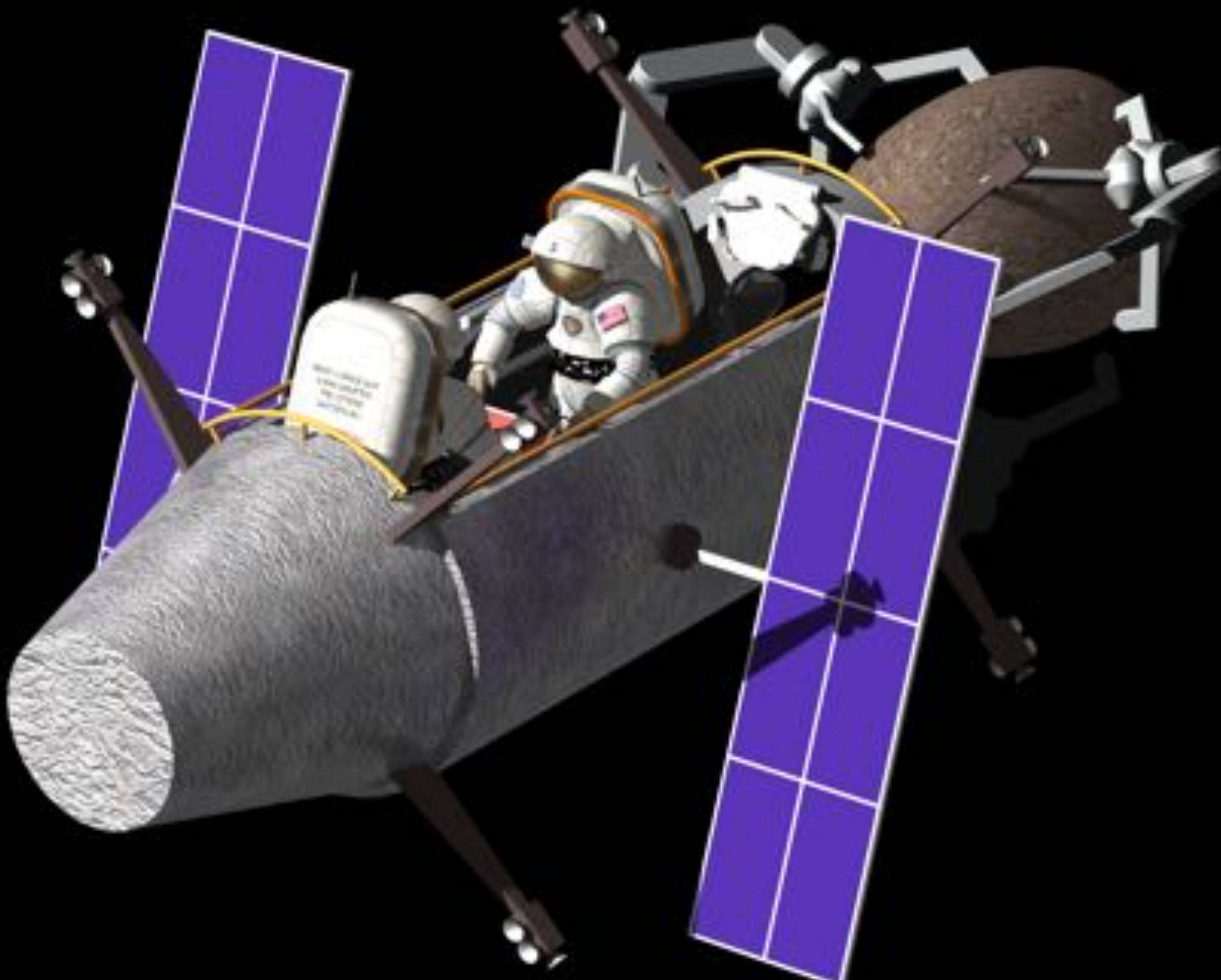


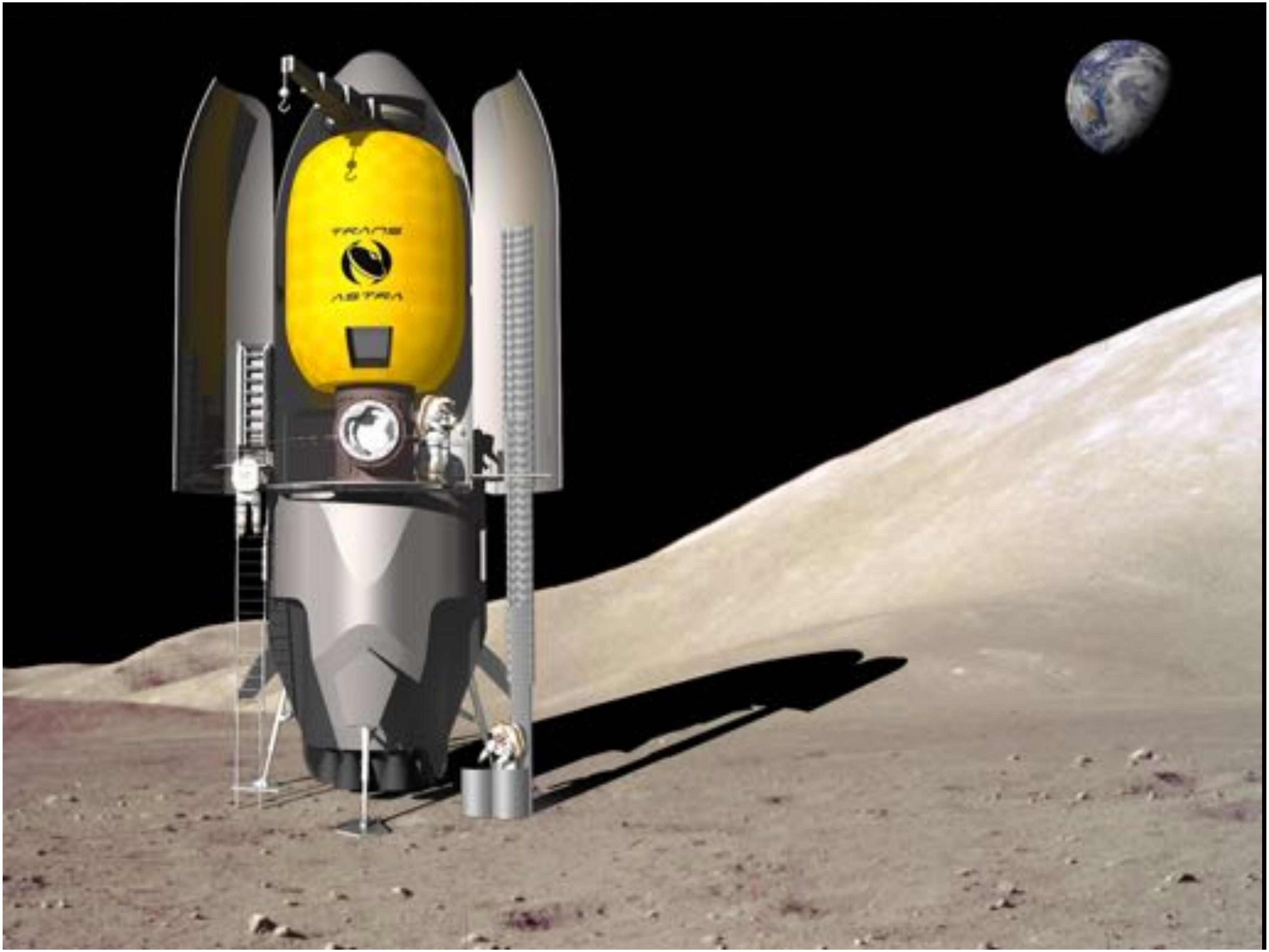
Image shows configuration with Worker Bee™. Reusable Spaceship OTV used in LOX-LM option.

# EVA At Small Asteroid With Scooter System



# EVA Boulder Transport With Scooter System

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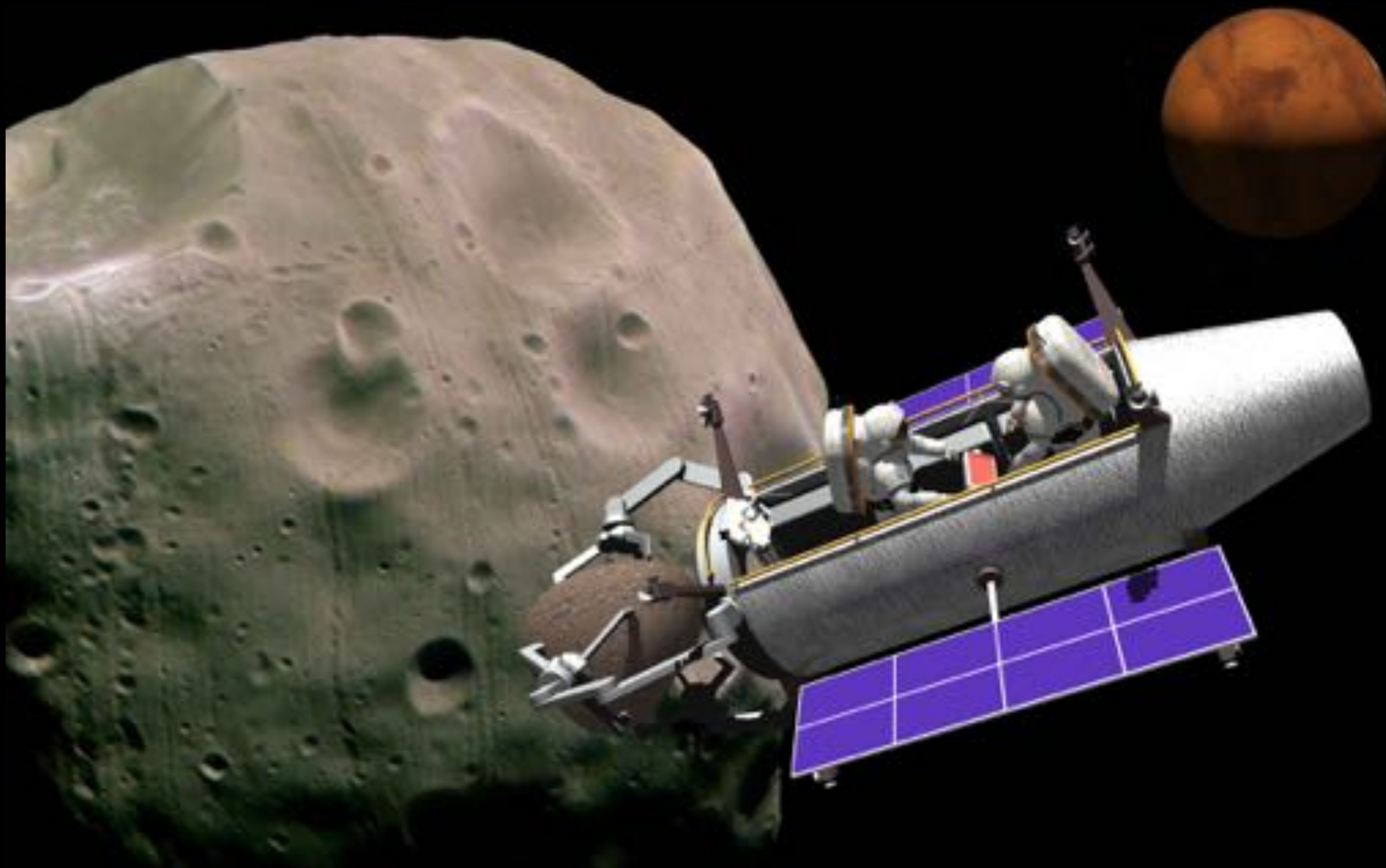
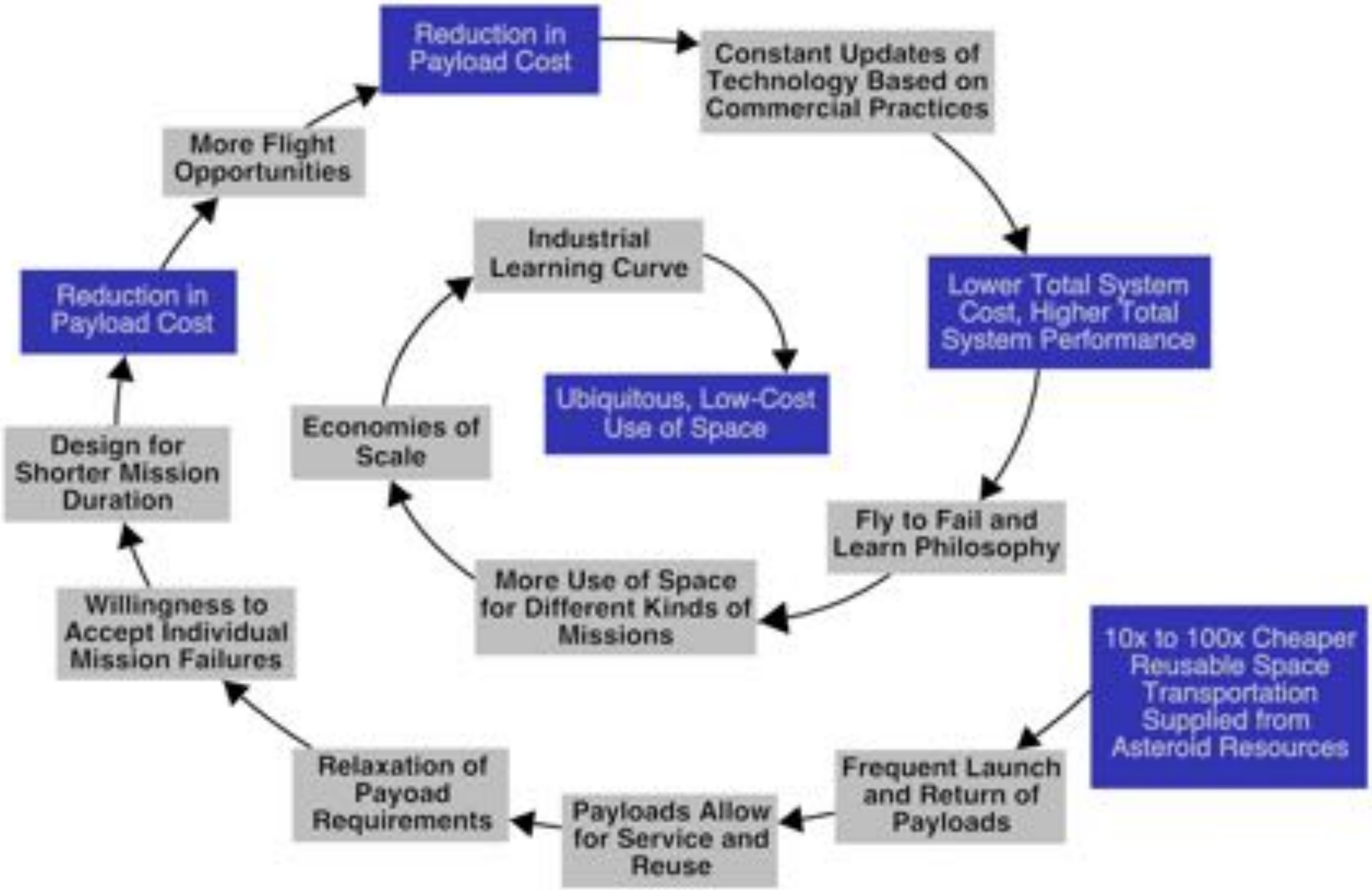
# Mars Exploration Systems at Deimos

# Mars Exploration Systems at Deimos

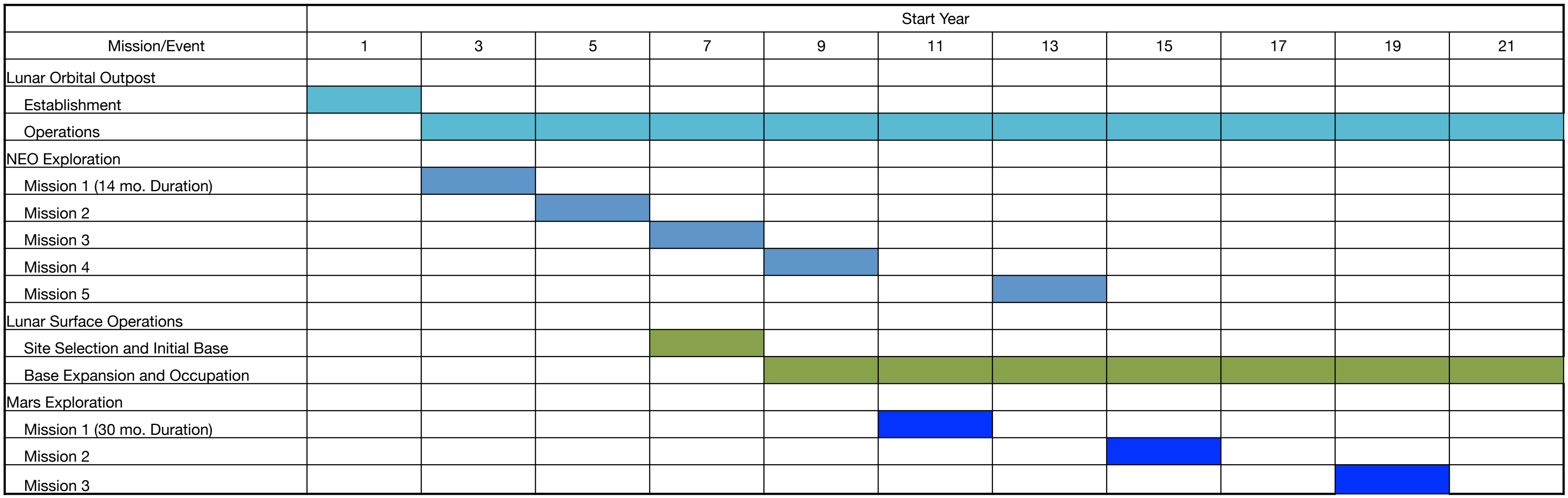


# Reusable Spaceship on Mars

# What This Gives Us



# Integrated Mission Schedule




- Example of how missions might be scheduled over a 20+ year span.

- Used to determine the number of active Honey Bees™ required over time and to provide for a summary across all NASA Human Exploration mission scenarios.
- Did not explore SLS/Orion options as preliminary analysis showed only one mission type possible under any reasonable budget

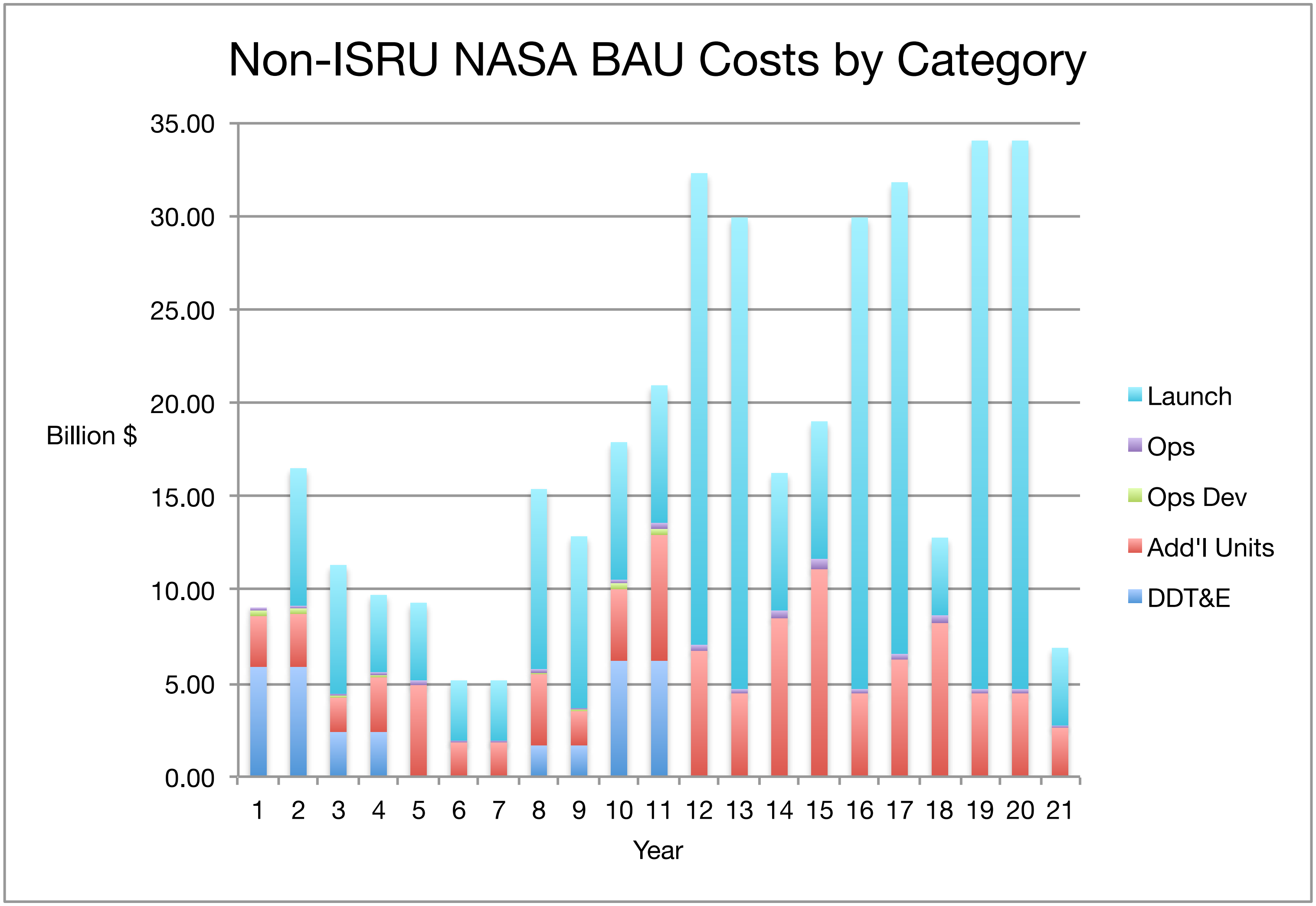
# Cost Modeling Assumptions

- NASA PPP Based on COTS and Related Programs
  - 1/3 -2/3 cost share
  - The 1/3 is financed
- Robotic systems costed using NASA cost model
- Human space systems costed using Claybaugh approach
  - Accurately reflects SpaceX development price to NASA for commercial
  - Accurately reflects STS and ISS development costs for BAU
- DDT&E Through First Two Units As Per Models
- Subsequent units @ 90% learning curve

Four Approaches:
- PPP vs BAH
- ISRU vs Launch From Earth

# Cost Model Results

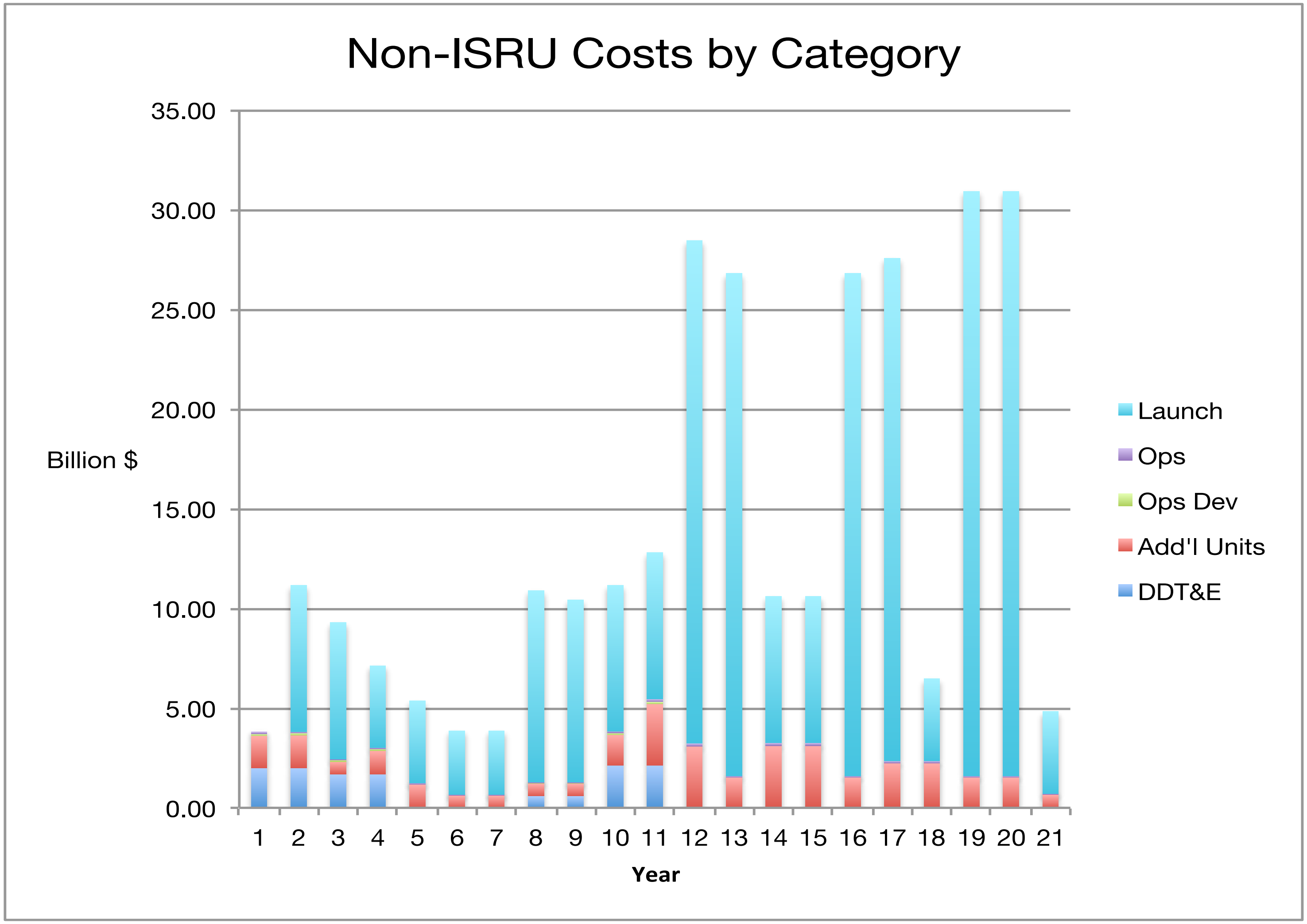
## 20 Year Summary – NASA Business as Usual no ISRU




**Unaffordable: Requires Doubling the NASA Budget**

# Cost Model Results

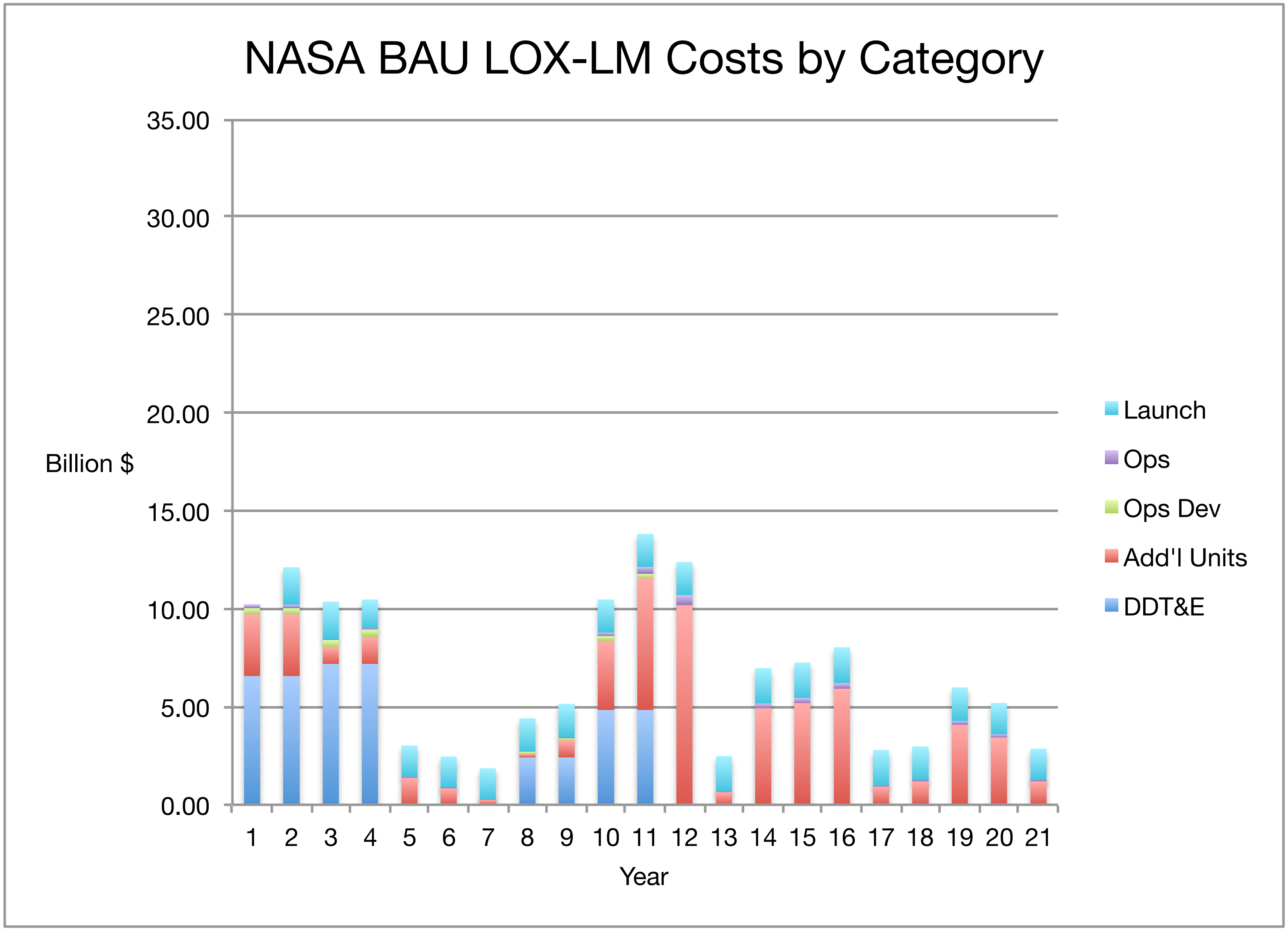
## 20 Year Summary – Best Commercial Practices, no ISRU




**Unaffordable: Requires > 50% Increase in NASA Budget**

# Cost Model Results

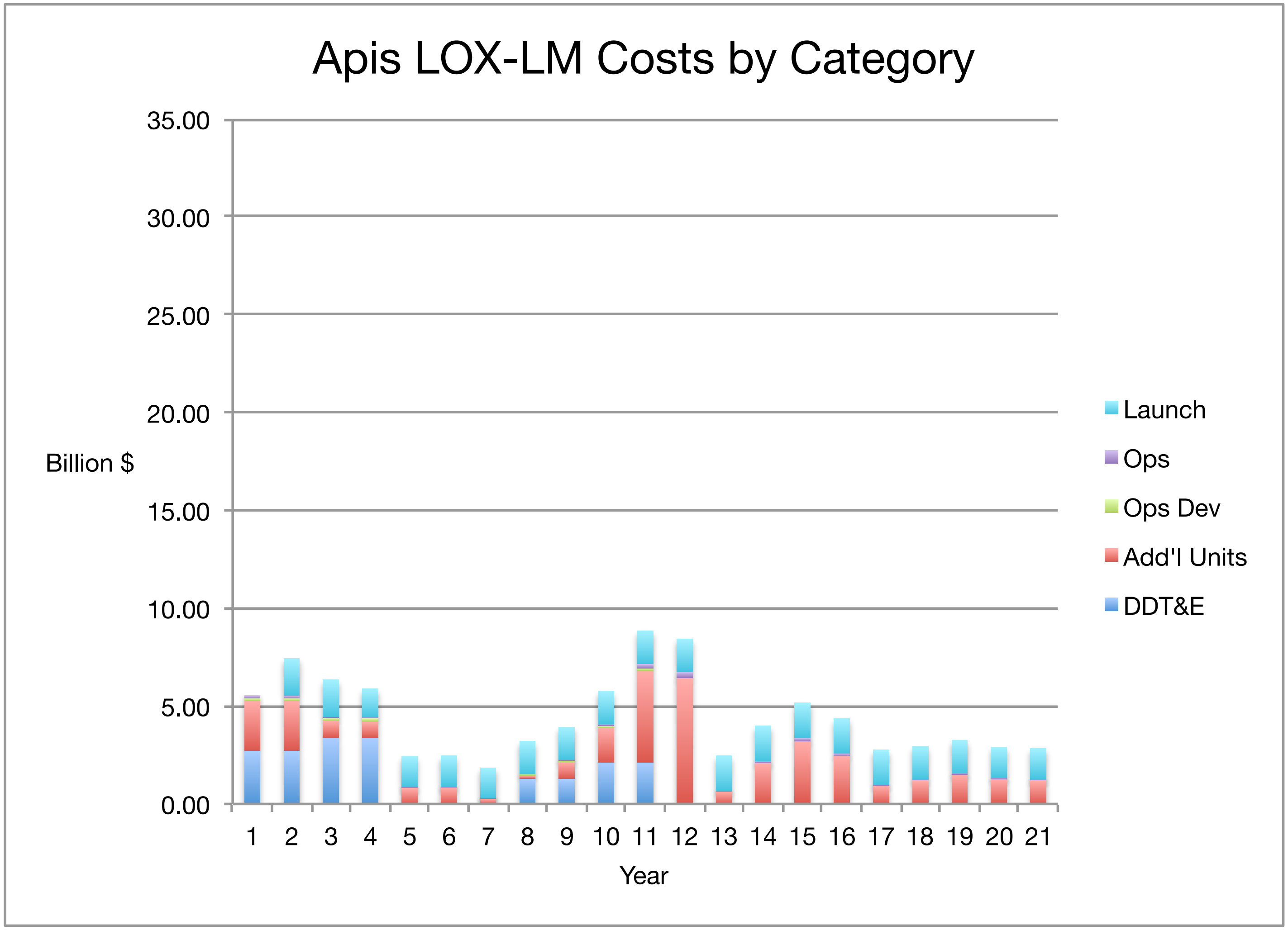
## 20 Year Summary – NASA Business as Usual with ISRU




**Marginal: Requires ≈ 30% Increase in NASA Budget**

# Cost Model Results

## 20 Year Summary – Best Commercial Practices



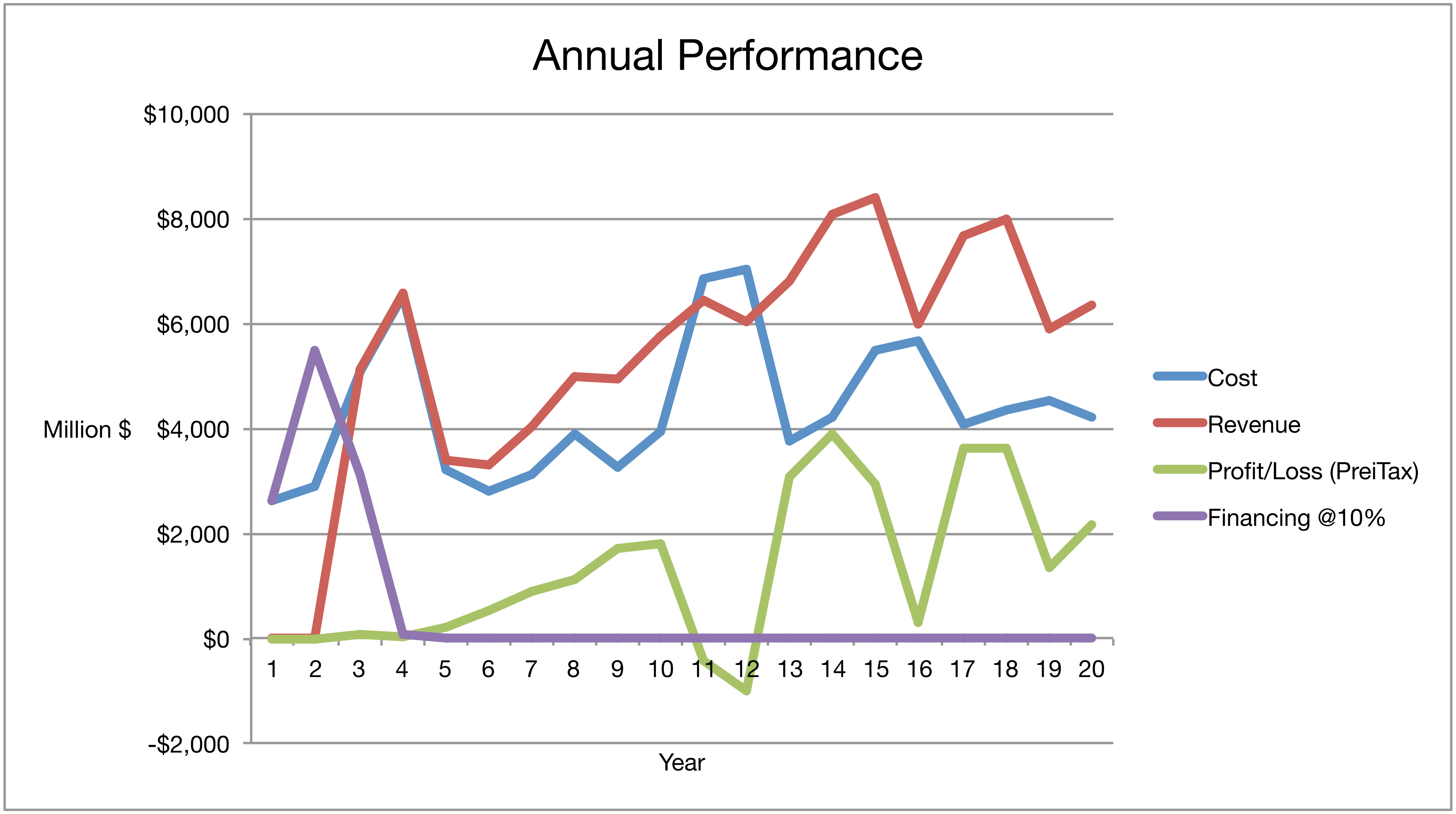

Affordable Within Congressional Guidelines

# Summary of Cost Analysis Results

| | Total Cost $B | Savings $B | Comments |
|---|---|---|---|
| **NASA Business As Usual, Supply From Earth** | ~400 | 0 | Unaffordable: requires doubling the NASA Budget |
| **Commercial Business Practices, Supply From Earth** | ~309 | ~90 | Unaffordable: requires > 50% increase in NASA Budget |
| **NASA Business As Usual, Asteroid Resources** | ~150 | ~250 | Marginal, Requires ≈ 30% increase in NASA budget |
| **Commercial Business Practices, Asteroid Resources** | ~95 | ~305 | Affordable, Average NASA Human Exploration Budget ≈$6B Annually, Fits Within Congressional Guidelines for HEOMD. |

Required: Major Shift to PPP for Deep Space Transportation Plus Massive ISRU

# TransAstra Minimum Business Case: Summary of Costs and Revenues

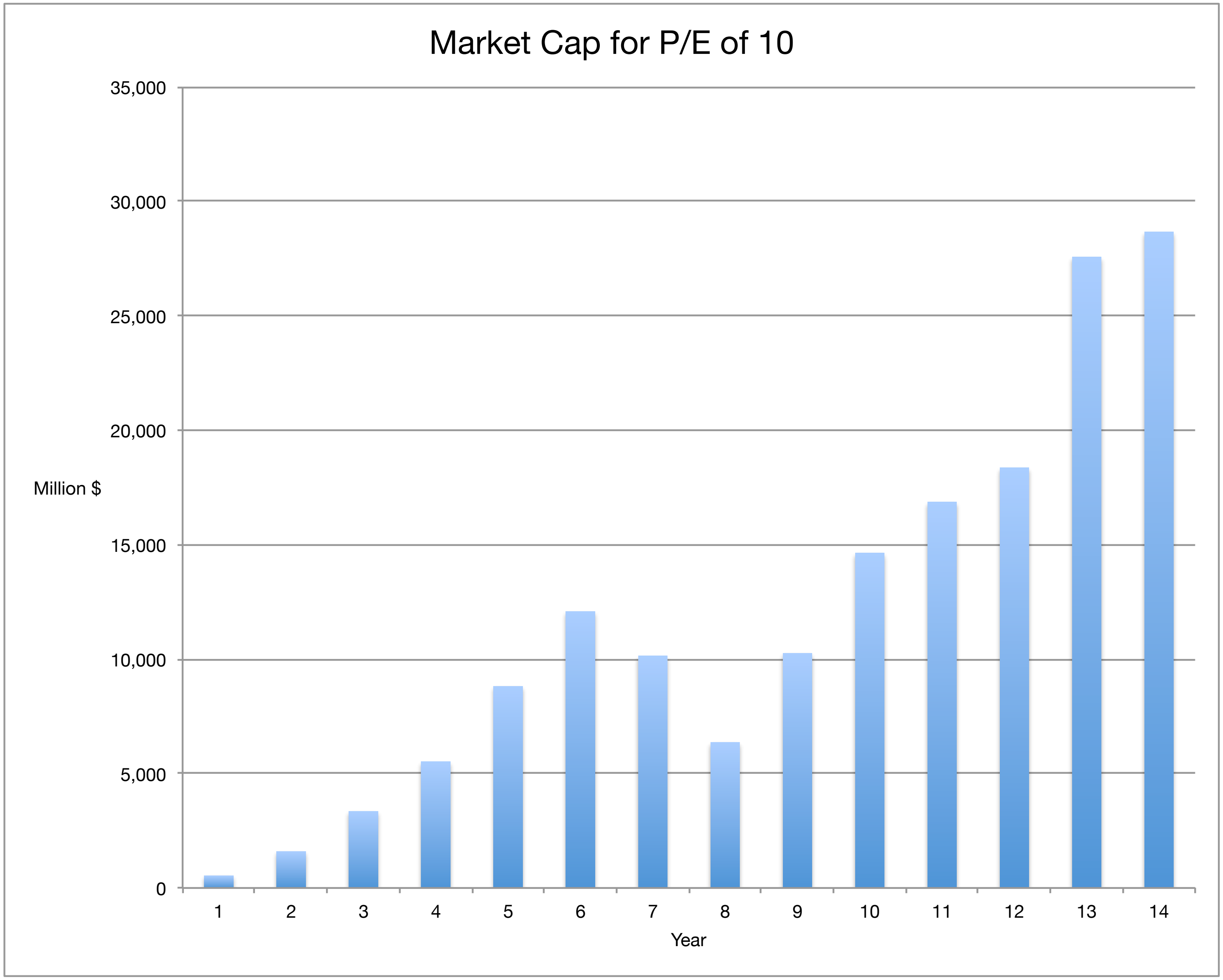


# Business Case: Transportation Service Price Analysis

- Propellant cost based on:
  - Honey Bee™ Unit Cost: 174 M$ (DDT&E TFU=$1.7B)
  - Honey Bee™ lifetime: 10 years
  - Honey Bee™ lifetime number of trips: 7
  - Replacement Asteroid Capture System (each): 20 M$
    - 6 will be required over the lifetime.
  - Replacement Inflatable Systems (each): 10 M$
    - 2 will be required over the lifetime
  - Initial Launch Cost: 63 M$ (Falcon 9)
  - Mass returned per trip:  100,000 kg on average
  - Average Propellant production from Mass returned: 60,000 kg
  - Total Lifetime Propellant production: 420 MT
  - Honey Bee™ lifetime costs: 174 + 120 +20 +63 = 377 M$
  - 377/420 = 748 $/kg Propellant Cost
  - Price is 748 $/kg + 20% or 897 $/kg

Cost to LEO would be $3,000/kg, Cost to LDRO would be $12,000/kg

# TransAstra Projected Market Cap Based on Five Year Forward PE 10:1



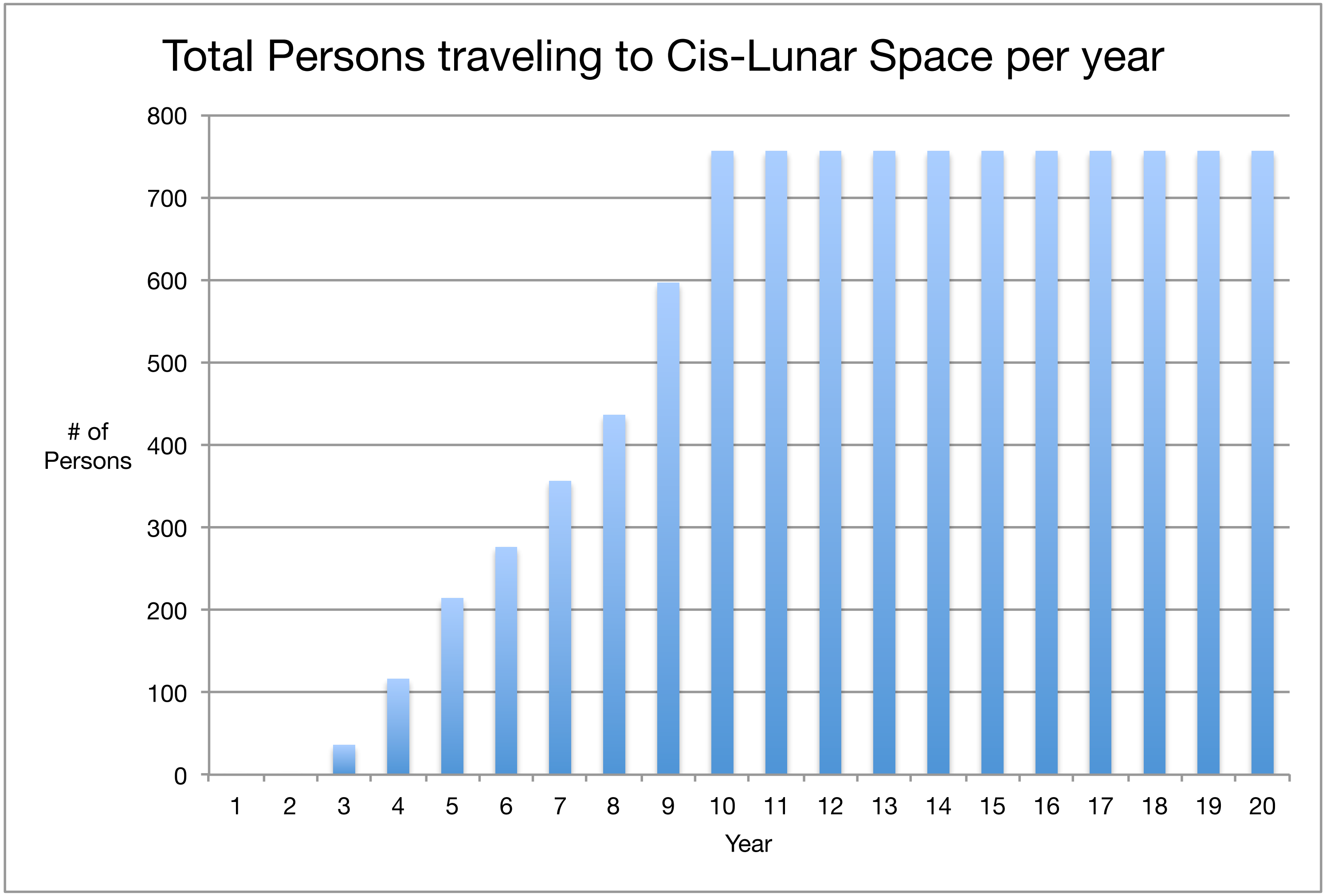
TRANS ASTRA

# Space Tourism Market:
# Very High Net Worth People

# Human Cislunar Transportation Fee Analysis

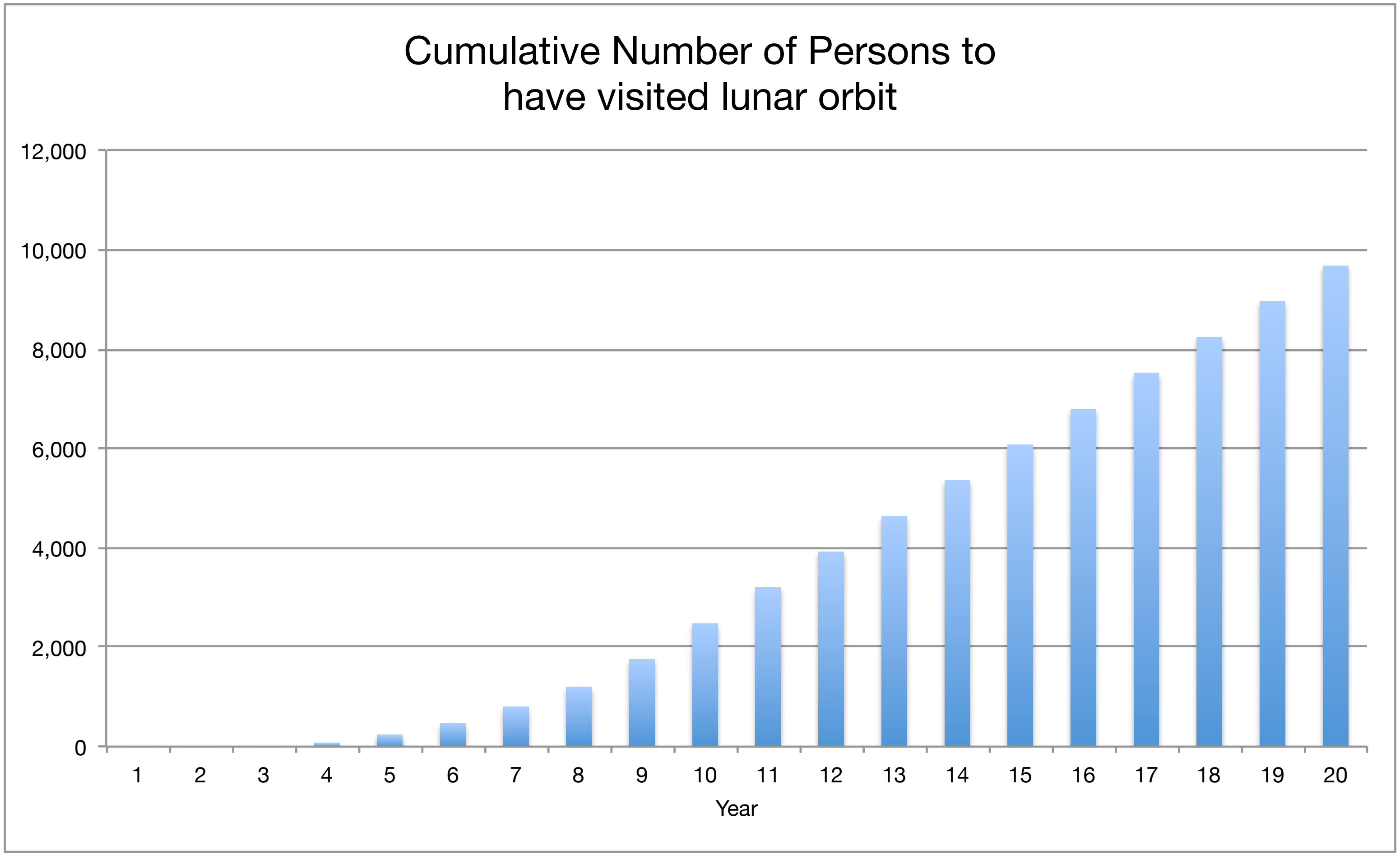
- Price per trip determined to be 60 M$ for 20 passengers or $3M each, not including Launch costs
- A 20 person passenger module is compatible with a reusable medium class 2nd stage ≈ Next Gen Falcon 9 or New Glenn

# The Next Market: Cislunar Tourism




Ramps to 40 Per Year Cislunar Excursions for 20 People

# Tourism Market Projection




Post Apollo

# Findings

- NASA's ambitions in the area of deep space human exploration are not affordable with a realistic budget close to $20B/yr (2017 dollars) ***without fundamental change***.
- Two fundamental changes can enable an exciting program of human exploration:
  - Public Private Partnership (PPP)
  - Asteroid ISRU.

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# Questions?

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