Journey to a Metal World

Critical Design Review: 15 March 2022

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01

Preliminary

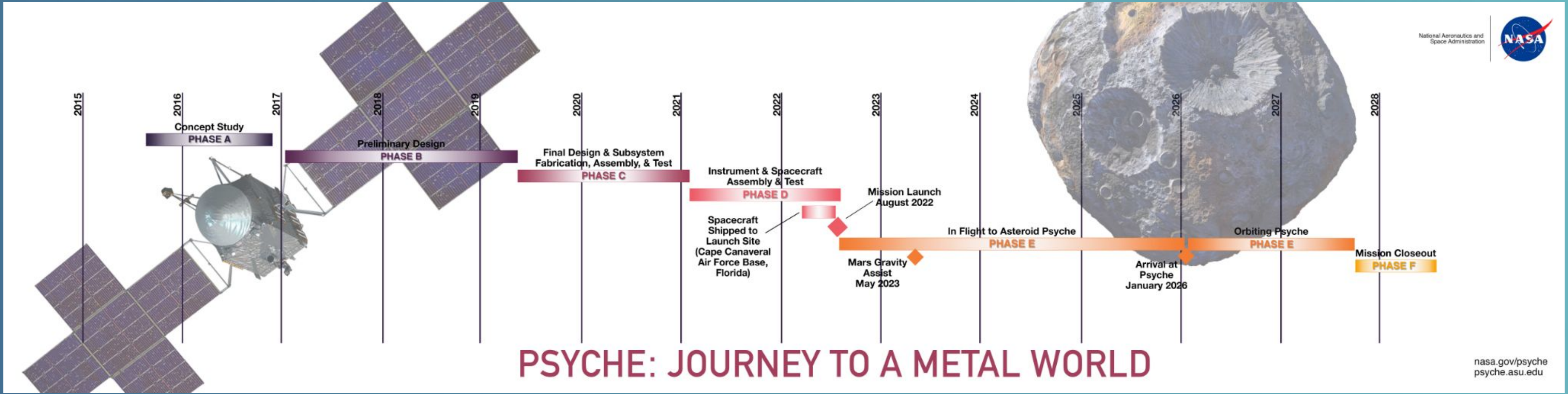
Psyche Mission and Spacecraft Overview

Psyche Mission and Spacecraft Overview

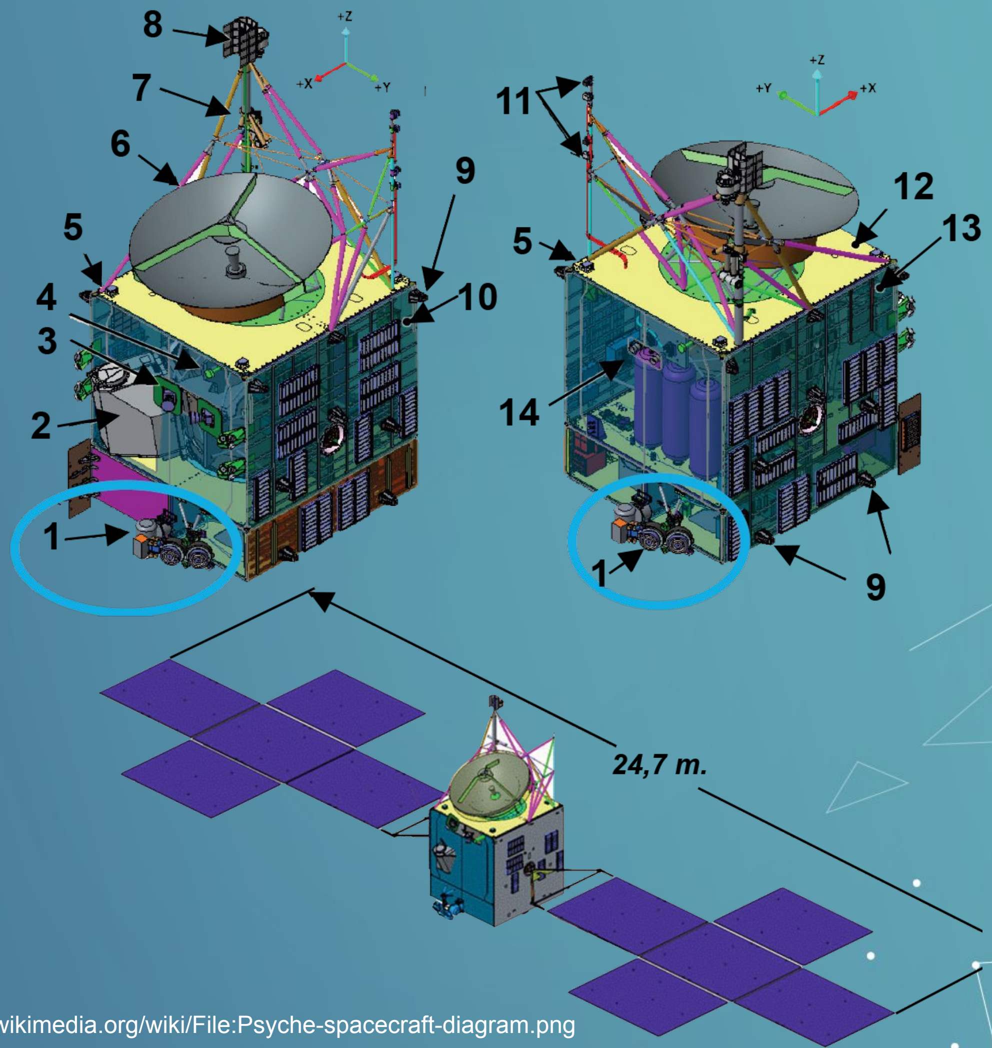
High Level:
The discovery of a planetesimal could offer insight into Earth’s hidden core.

Stakeholders:
NASA/JPL, ASU, Maxar Technologies, John Hopkins University, Technical University of Denmark (DTU), MIT, United States Taxpayers

Mission Timeline



Psyche Diagram



24.7 m long, 7.3 m wide
Bus: 3.05 m long, 2.44 m wide
Mission duration: 6 years
Dry mass 1470 kg
Wet mass 2634 kg

1: SPT-140 Thrusters
2: DSOC
3: Star Trackers
4: Low Gain Antenna
5: Sun Sensor
6: X-Band High Gain Antenna
7: Neutron Spectrometer
8: Gamma Ray Spectrometer
9: Cold Gas Thruster
10: +Y Panel
11: Magnetometer
12: Top Deck
13: -Y Panel
14: Multispectral Imagers

https://commons.wikimedia.org/wiki/File:Psyche-spacecraft-diagram.png

02

Modification Overview

Mission Extension

Mission Extension: Increasing Delta V

Motivation: Utilize spacecraft beyond current end of life

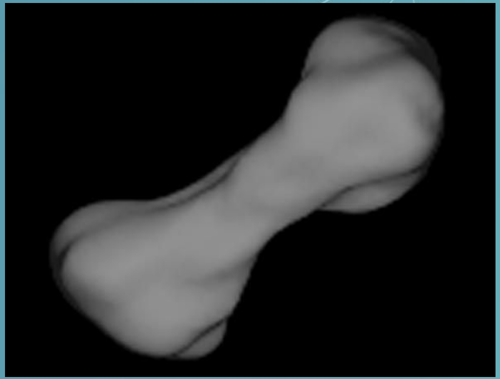
Intended Benefits: Extend data collection and exploration of Asteroid Belt

Analyses: Delta V/Orbital Destinations, Power, mass

Description: Delta V determines where spacecraft can go. Increased Delta V increases destination possibilities.

Destination: 216 Kleopatra

- Second largest M-Class asteroid
  - High metal content
- Radar albedo 0.43 ± 0.10
- Two orbiting moons
- Good candidate for Psyche Payload



https://apod.nasa.gov/apod/ap000510.html

Sources: https://echo.jpl.nasa.gov/asteroids/shepard.etal.2018.kleopatra.pdf
https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=2000216&view=OSPR

Modifications

1) Replace rigid solar arrays with roll out solar arrays and more efficient solar cells

2) Replace composite-overwrapped pressure vessel tanks with one larger one

03

Roll Out Solar Array

Power Analysis

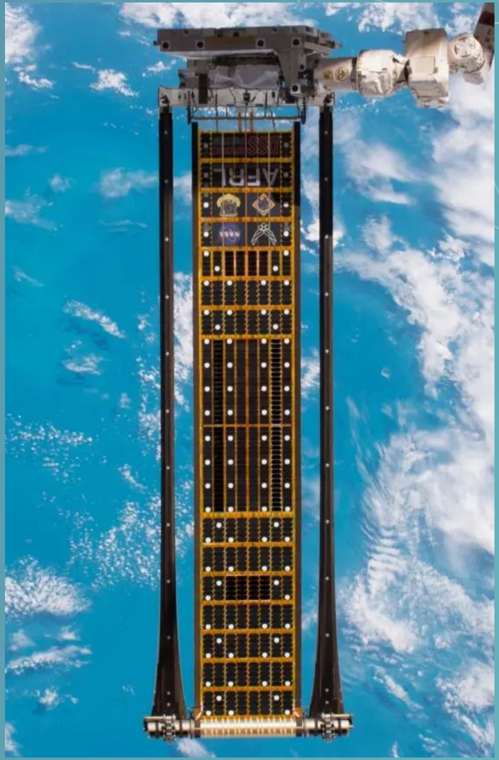
Modification: Roll out solar Array (ROSA)

Purpose: To increase power generation and thrust capability while keeping the same mass.

Motivation: Flexible solar arrays have become more attractive due to higher power density (W/m^3)

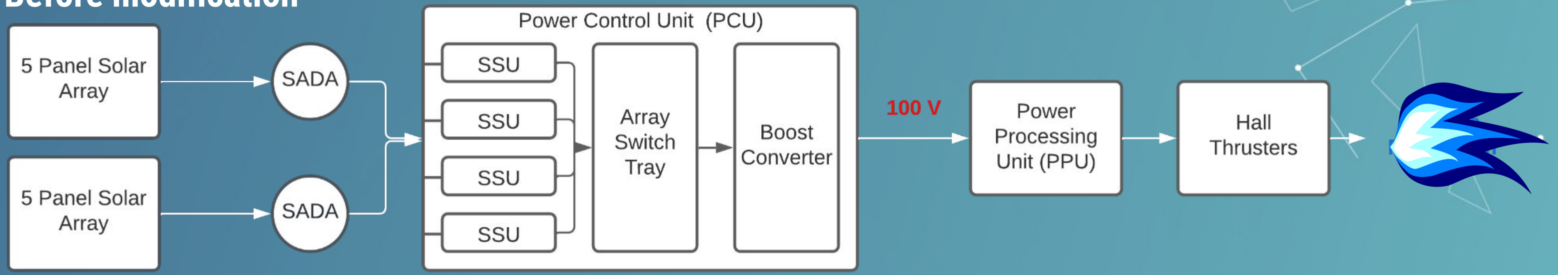
Benefits:

- Higher thruster efficiency
- Mission extension

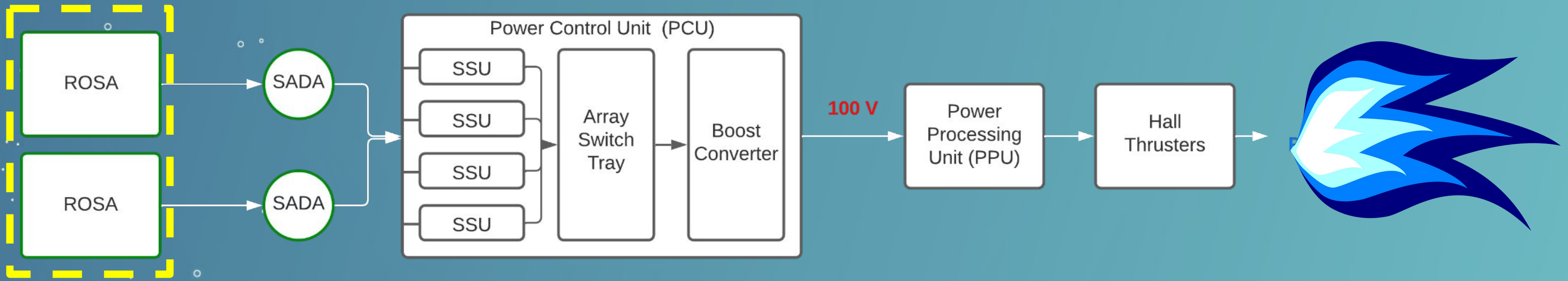


Solar Power to Thrust Relationship

Before modification



After modification



Assumptions

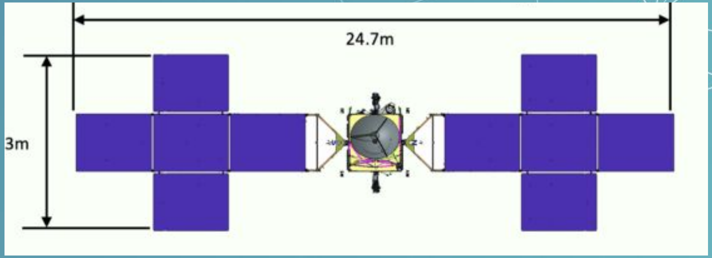
- Mass of solar cells staying the same

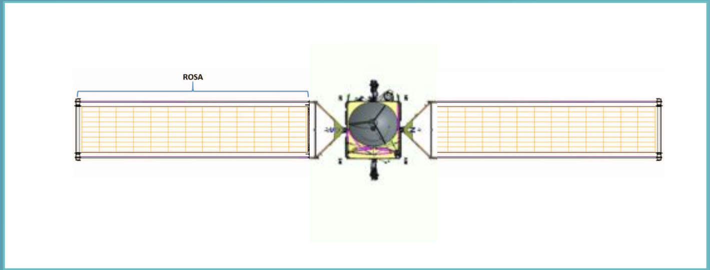
Cell type	ZTJ Triple Junction Cells	IMM-Alpha Solar Cell
Mass per unit Area	0.89 kg/m^2	0.49 kg/m^2
Total Area	62.2 m^2	107.45 m^2

- 900 W is required to operate the spacecraft bus throughout the mission

Comparison of New Specifications

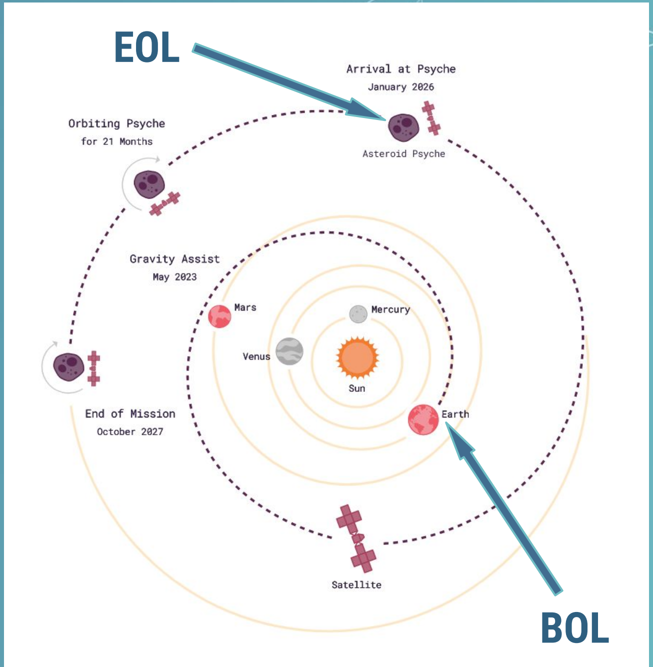
	10 Panel Rigid Solar Array	Roll Out Solar Array
Total Power	21 kW	48 kW
Total Area	62.7 m^2	107 m^2
Efficiency	29%	32%
Cell type	ZTJ Triple Junction Cells	IMM-Alpha Solar Cell





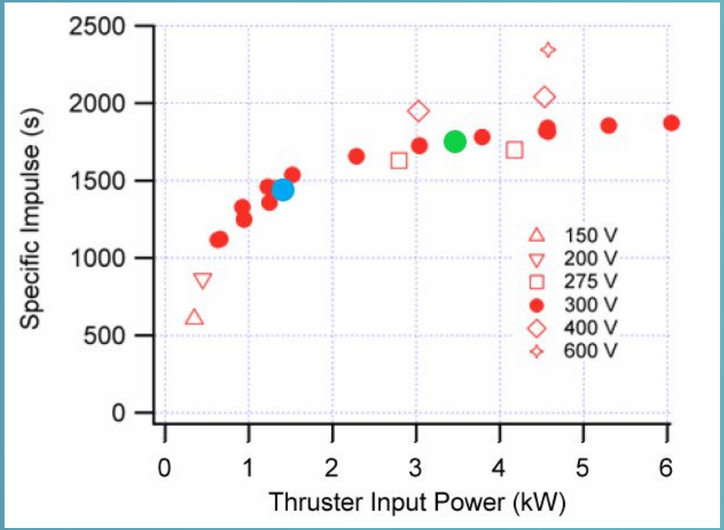
Comparison of Beginning of Life (BOL) & End of Life (EOL) Power

	10 Panel Rigid Array's	Roll Out Solar Arrays
BOL (1 AU)	21 kW	48 kW
EOL (3 AU)	2.3 kW	4.3 kW
Bus Power	900 W	900 W
EOL Available Power for Thrusters	**1.4 kW**	**3.4 kW**



Specific Impulse of Thruster

- Increased Power at Psyche increases Isp
  - 1.4 kW = 1450 s (Blue - Rigid Arrays)
  - 3.4 kW = 1750 s (Green - ROSA)



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Xenon Storage Tanks

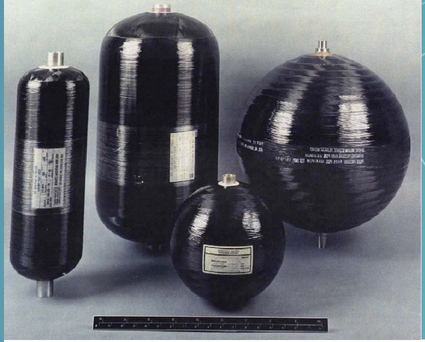
Mass Budget Analysis

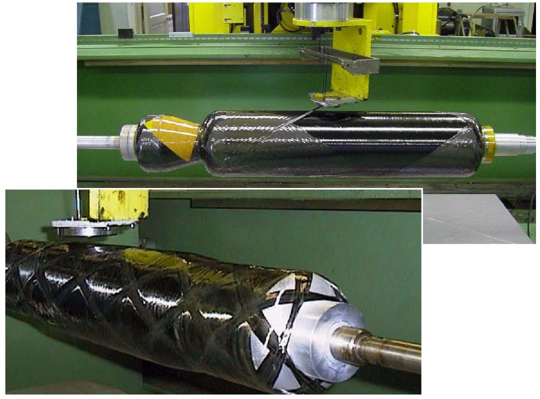
Composite-Overwrapped Pressure Vessel (COPV)

Current Tanks are COPVs
- Inner liner of Titanium
- Fiber overwrap (Carbon Fiber)
- Extremely light and strong

Psyche uses 7 82L COPVs
- Each Tank has a volume of 82L (574 L Total)
- Storage Pressure is 187 bar (1.87E7 Pa)
- Storage Temperature is 45 C (315K)
- Total Xe mass storage of 1085 kg

Each Tank Mass is 11.11 kg
- 77.79 kg Total



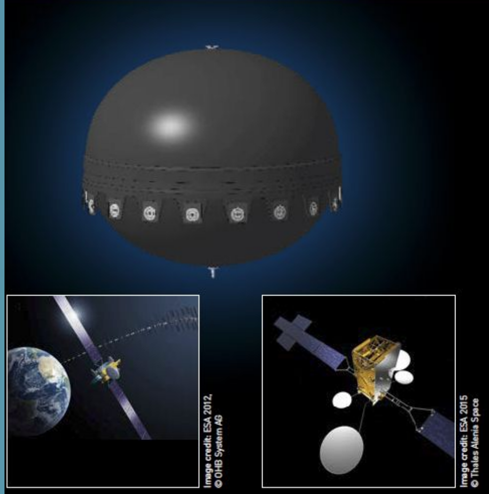


Use One Larger COPV to Reduce Mass

- L-XTA 600 from MT Aerospace
- Under Qualification
- 600 L Single Tank
    - 26L more capacity than current design
    - Mass of 68 kg
    - 9.79 kg less massive than 7 tanks
- Mass Savings Put into additional Xenon fuel

L-XTA / 300-900 Family

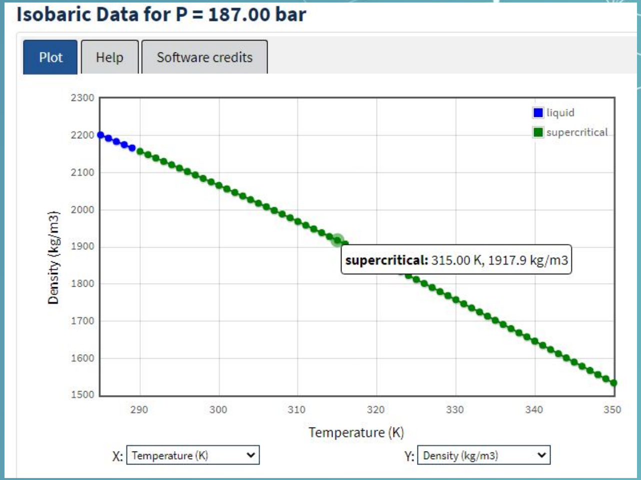
Xenon Tank – Electric Propulsion (EP)



HERITAGE			under Qualification
FLUIDS			Xenon
MATERIALS	Shell		Ti-6Al-4V
	Tube		Ti-3Al-2.5V
	Overwrapped		Epoxy-based CFRP / T800
MOUNTING INTERFACE			equatorial skirt
TOTAL VOLUME		600 - 900 l	36.614 - 54.921 in³
TEMPERATURE RANGE		up to 50 °C	up to 122 °F
TANK DRY MASS		68 - 85 kg	149,9 - 187,4 lbs
DIAMETER		1.144 mm	45,04 in
LENGTH		979,3 – 1306 mm	38,56 – 51,42 in
MEOP*		187 bar	2.712 psi
PROOF PRESSURE (x 1,25)		233,8 bar	3.390 psi
BURST PRESSURE (x 1,50)		280,5 bar	4.068 psi
BURST PRESSURE TESTED		bar	psi

Mass Budget Analysis

- Verify mass of propellent stored in new, larger tanks
  - Density Determined From NIST Website
  - 1917.9 kg/m^3 For Xenon at 187 Bar and 315K
  - 0.6 m^3 Tank gives a maximum 1150 kg Xe
- Original Tanks Carry 1085 kg Xe
  - Add the additional 9.79 from tank mass savings
  - Total Xe mass at launch 1094.79 kg
- Psyche mass remains at its original value



Original Propellant Mass Budget

- Mass Information overall was very sparse. PDR Propellent mass budget is only available information.
- Cruise uses the most propellent mass
- Most of cruise is at optimal thrust conditions
  - Powered at 4.5 kW
  - Isp of 1800+ seconds
- Re-Analysis for (16) Psyche capture through Orbit D

Table 1. Xenon Propellant Budget at Project PDR.

Usage Category	Propellant Allocation, kg
Deterministic Cruise	885.0
Cruise Momentum Management	5.0
Capture to Orbit A	6.4
Orbit Transfer: A to B	2.4
Orbit Transfer: B to C	1.8
Orbit Transfer: C to D	15.8
Orbit Maintenance	2.5
Non-Usable Propellant (residuals, leakage, fill error, thruster startup/shutdown, initial checkout)	38.9
Margin: Missed Thrust	35.4
Margin: Thruster Performance Uncertainties	36.8
Total	**1030.0 kg**

Re-Constructing Delta-V

$$\Delta V = I_{sp} g_0 \ln\left(\frac{m_i}{m_f}\right)$$

- Utilizing Propellent mass budget from PDR
- Reverse Calculated Delta-V
  - Use approximate Isp of 1450
  - Capture to Orbit D
- Calculate new mass use
  - Use approximate Isp of 1750
- Add Xe mass savings from COPV
- Add Xe mass excess
- Remaining Xe mass 69.7 kg

assume cruise uses the same amount of propellent in both configurations						
Dry Mass kg	1470					
Initial Xe mass kg	1085					
N_2 Mass initial	79.3					
Total Mass	2634.3					
Usage Category Propellant	Propellent Mass (kg)	Total mass remaining	Delta-V required (m/s)	Total Mass Remaining (Proposed)		
Deterministic Cruise	885	1749.3	NA	1749.3		
Cruise Momentum Management	5	1744.3	NA	1744.3		
Capture to Orbit A	6.4	1737.9	52.28700391	1738.995473		
Orbit Transfer: A to B	2.4	1735.5	19.65728418	1737.005412		
Orbit Transfer: B to C	1.8	1733.7	14.76081073	1735.512557		
Orbit Transfer: C to D	15.8	1717.9	130.228688	1722.397168		
Orbit Maintenance	2.5	1715.4	20.71549604	1720.320058	4.920057545	
Non-Usable Propellant (residuals, leakage, fill				1609.220058	14.711149	Total increased propellent mass at completion of initial mission
error, thruster startup/shutdown, initial checkout)	38.9			1577.500058	69.711149	Xe Remaining at primary mission completion
Margin: Missed Thrust	35.4					
Margin: Thruster Performance Uncertainties	36.8		detla V available	775.9207541		
Total 1030.0 kg	1030					
Isp	**1450**			**1750**		
Total Xe Mass gained (kg)				14.711149		
Original Excess Xe (55 kg)				55		
Remaining Xe at completion of primary mission				**69.711149**		

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Mission Extension

Delta-V Requirements and Budget

Delta-V

- Calculate Available Delta-V at End of Primary Mission
- Xe remaining: 69.7 kg
- Mass of spacecraft 1720.32 kg
- Isp 1750
- Total Delta V of 783.9 m/s remaining

$$\Delta V = I_{sp} g_0 \ln\left(\frac{m_i}{m_f}\right)$$

Mission Extension: Principles

- Orbital Mechanics
  - Forces from planets
  - Four orbit types
    - Circular
    - Elliptical
    - Parabolic
    - Hyperbolic
- Patched Conic
  - Successive two body problems

Mission Extension: Assumptions

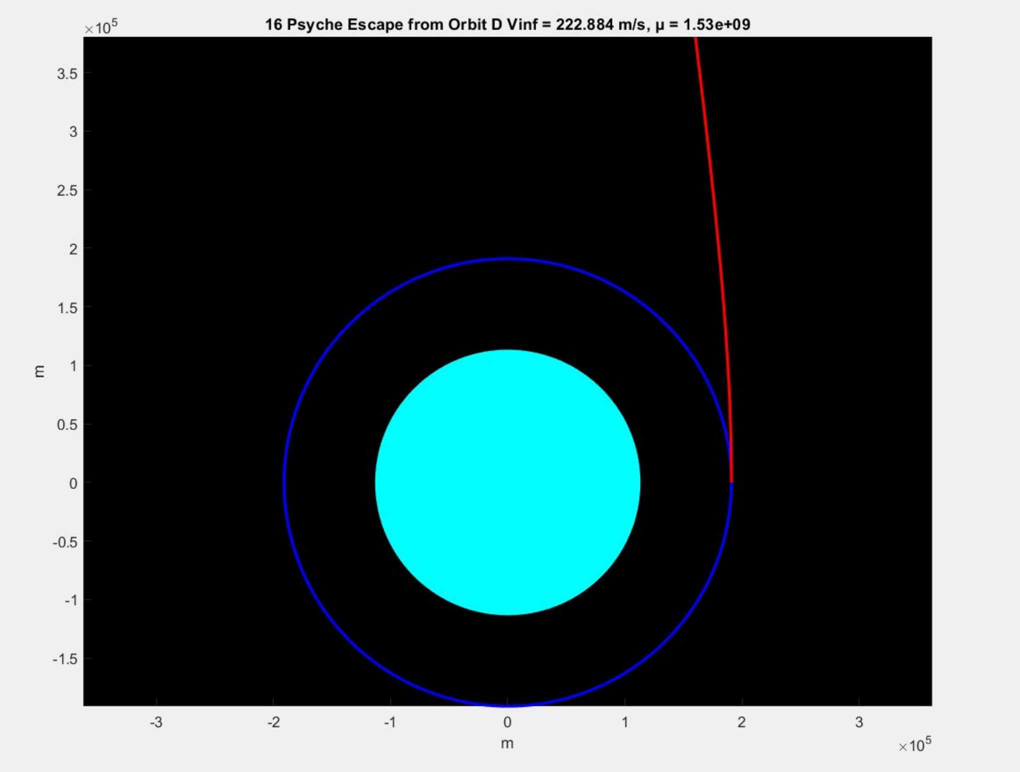
- Instantaneous change in velocity
- Parallel exit velocity with planet
- Sphere of Influence
- Patched Conic (two body assumption)
- Timing chosen st. asteroid position is ideal
- 2D plane

Mission Extension: Math

$$V_{escape} = \sqrt{\frac{2\mu}{r}}$$

$$V_{oberth} = \sqrt{V_{esc^2} + V_{inf^2}}$$

Mission Extension: Results



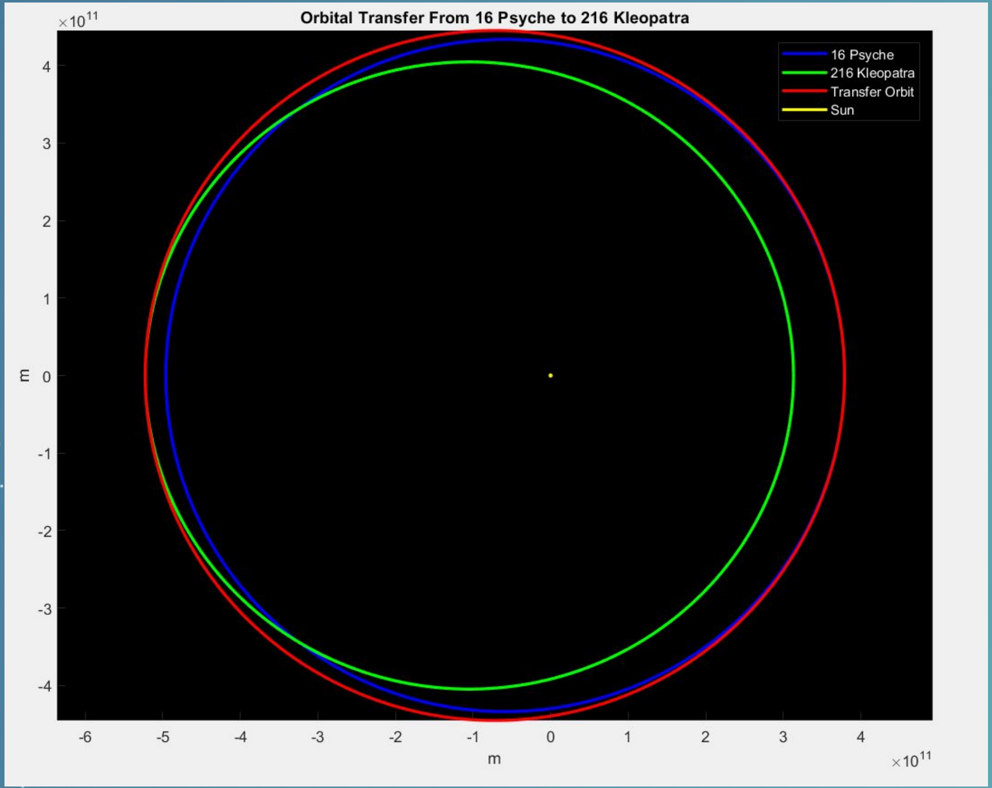
Mission Extension: Math

$$r_{p_{Transfer}} = r_{p_{16}}$$

$$r_{a_{Transfer}} = r_{a_{216}}$$

$$V = \sqrt{\mu(\frac{2a - r}{ar})}$$

Mission Extension: Results



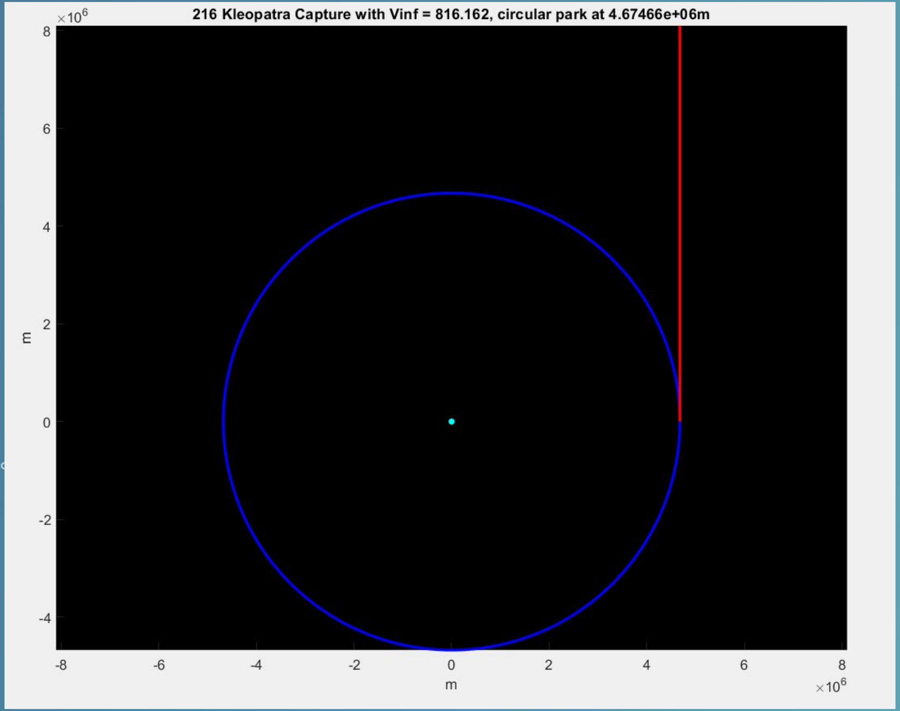
Mission Extension: Math

$$r_{SOI} = a\left(\frac{m_2}{m_1}\right)^{0.4}$$

$$b = r_{planet}\sqrt{1 + \frac{V_{esc}^2}{V_{inf}^2}}$$

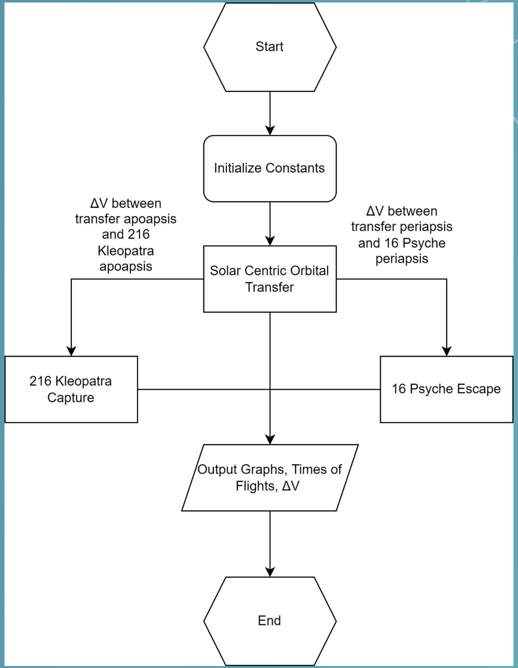
$$d = r_{SOI}\cos(\phi)$$

Mission Extension: Results



Mission Extension: Code

- Matlab script
- Custom functions for escape, transfer, and capture
- Order of operations
- Orbital data from JPL's small body database lookup



Mission Extension: Results

- The escape phase requires 166.815m/s and takes 22.8189 hr
- The Hohmann transfer phase requires 0m/s and takes 955.293 days
- The capture phase requires 808.063m/s and takes 2.73438 hr
- The entire mission (escape to capture) requires 974.878m/s and takes 2.62016 years
- Orbit A: 811 km
- 216 Kleopatra end: 4,675 km (5x larger)

Mission Extension: Discussion

- Weakness: ΔV not instantaneous
- Solution: Re-derive differential equations to include force of thrust in two-body assumptions
- Assuming thrust parallel to radius:

$$\ddot{x} = \left(\frac{-G\mu x}{r^4} + \frac{F_{thrust,x}}{m_2}\right)$$

$$\ddot{y} = \left(\frac{-G\mu y}{r^4} + \frac{F_{thrust,y}}{m_2}\right)$$

Mission Extension: Discussion

- Importance:
    - Smaller margin of error than first believed (and calculated!)
    - With space flight advances and more space certified parts, this mission is within the realm of possibility

6

Testing

Validation of Design Changes

Electric Performance Test

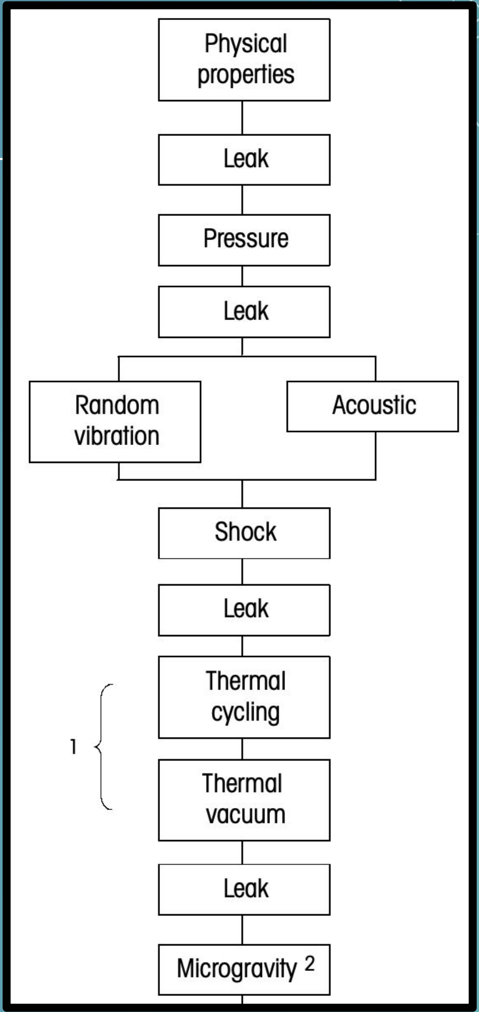
Goal & Requirement: Mission Extension >> Increase Delta V

Modification Requirement 1:

- ROSAs must produce 4.3kW of power EOL

Plan:

- Perform electrical functionality testing before environmental tests as a golden reference and then after for validation
-



ECSS Structural Testing

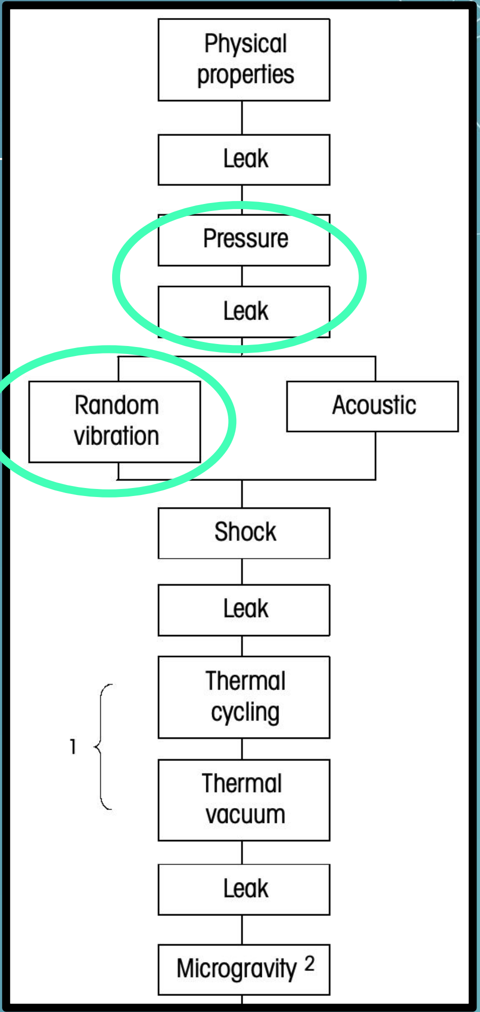
Goal & Requirement: Mission Extension >> Increase Delta V

Modification 2:

- The COPV tank must hold 1094 kg of propellant and must be durability standards

Plan:

- ECSS Structural Testing



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Conclusions

Final thoughts

Final Remarks and Intuition

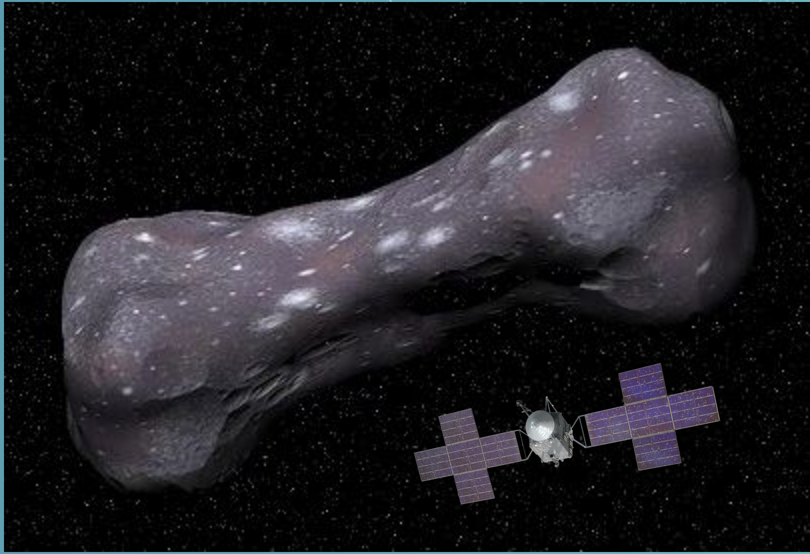
Goal & Requirement: Mission Extension >> Increase Delta V

Modifications:

1) Twin 5 Panel Arrays >> Roll Out Solar Arrays
2) 7 COPVs -> 1 COPV

Analysis: Not enough Delta-V to complete mission

** Additional 55 kg Propellent Would Fit in our tank
If we added this propellent we would have an additional **1464 m/s** of delta-V available



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Special Thanks to:
Professor Robinson
Janine Moses
Daniela Ivey

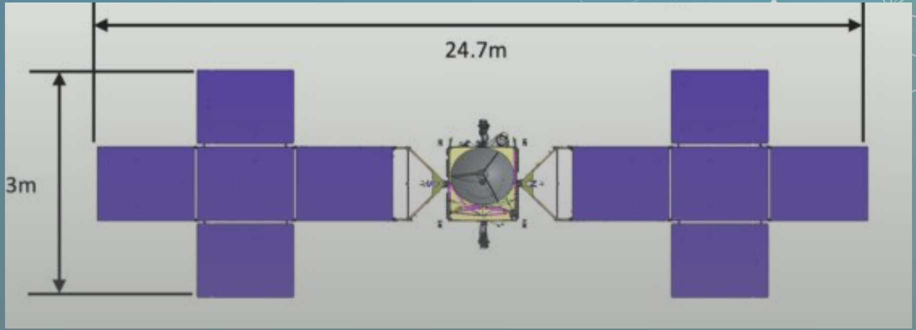
Any Questions?

Current Solar Array Layout - Before changes

Twin - 5 panel rigid solar arrays made of graphite composite
Total active area of 62.6 m^2

Under AM0 conditions:
Efficiency of 29.5%
Produces 19.2 kW at 1 AU

At Psyche conditions, 3.3 AU and -105° C
Produces 2.4 kW



Rotated by single axis solar array drive actuators.

Power generated is send to Solar Array Drive Assemblies (SADA's) and sent to Sequential Shunt Unit (SSU)

Overview of Analysis: Power & Thrust

Description: **Understand how swapping the solar arrays will increase our Power generation**

Analysis tools, fundamental engineering concepts to be used

- Specific impulse

Analysis plan: **Analyze thrust during journey to (16) Psyche with new power generation.**

Results: Before and after comparison of specifications.