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# Solar System Exploration Augmented by In-Situ Resource Utilization: Human Planetary Base Issues for Mercury and Saturn

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**Bryan Palaszewski**
**NASA Glenn Research Center**
**Cleveland, OH**
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# Introduction

- Solar system exploration options.
- Why Mercury and Saturn?
- Mercury bases.
- Permanently shadowed craters and water ice.
- Saturn moon bases.
- Cryogenic methane oceans and water ice.
- Mercury system transportation.
- Saturn system transportation.
- Concluding remarks.

# Vision for human exploration

- Vast potential for new resources throughout the solar system.
- New cradles of humanity required for the survival of the species.
  - Avoiding natural disasters.
  - Recovery from such disasters.
- Human exploration allows new perspective on the human condition.

# Solar System Exploration: Now

- **Exploratory robotic flights throughout the solar system, somewhat infrequent.**
- **Phased investment in a narrow array of technologies.**
- **Travel times are long, transportation costs are high.**

# Solar System Exploration: Krafft Ehricke's Vision

- **Exploratory flights and then permanent human presence throughout the solar system.**
- **Phased investment in a wide array of technologies.**
- **Travel times, transportation costs reduced.**

# Krafft Ehricke's Vision

- Extensive exploration and exploitation from Mercury to Saturn.
- Power-rich and resource-rich industries.
- New off-world societies, new branches of humanity.
- New wealth for Earth and all humanity.
- Lunar and space industrialization are keys to Earth's progress.
- Limits to Growth are eliminated.

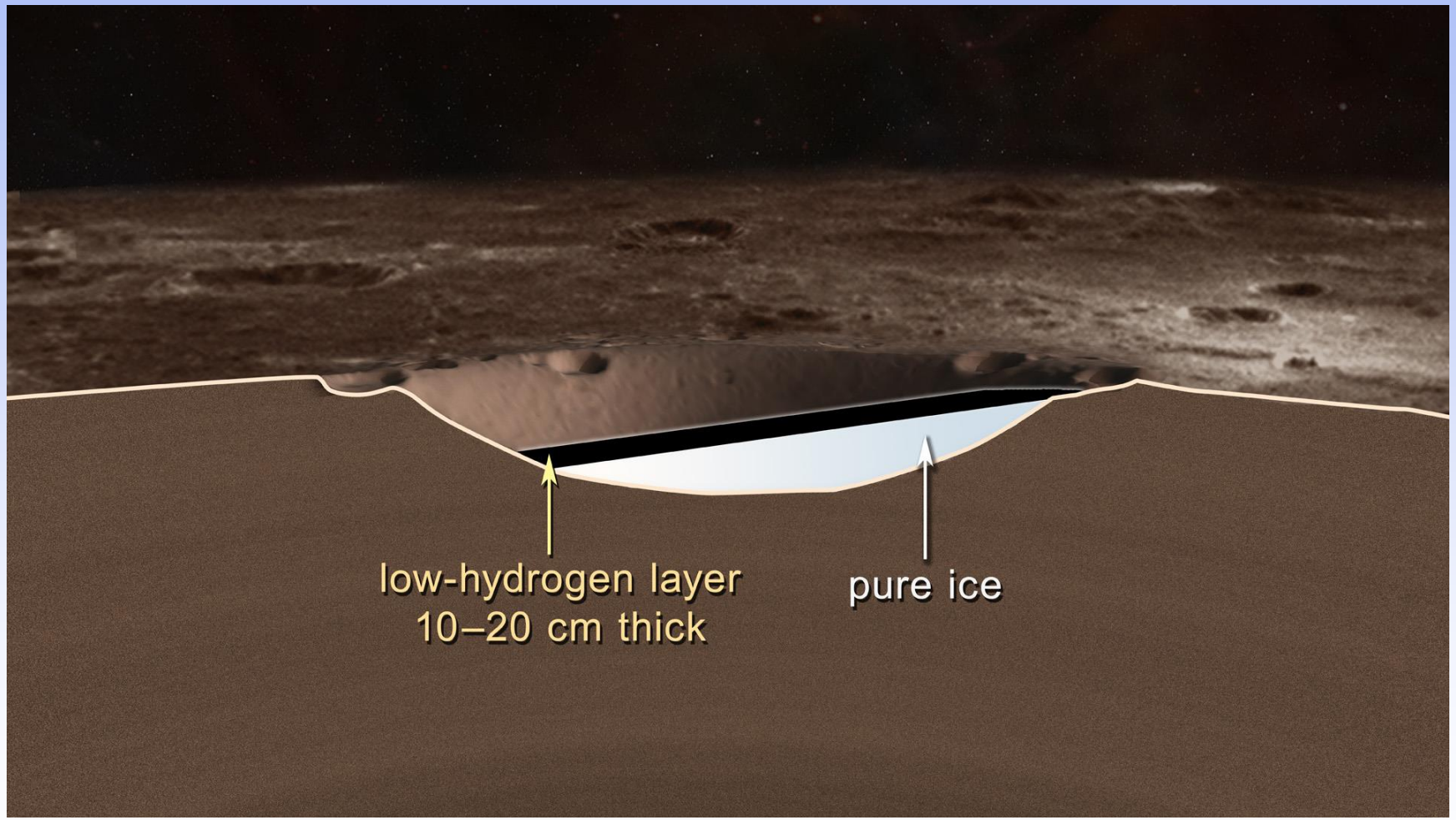
# Issues for long term space flight

- Exposure to microgravity.
- Development of artificial gravity.
- Exposure to space radiation.
- Protection against radiation.
- Spacecraft and tool operations for long term missions away from Earth based repair options.
  - Breakdown of systems.
- Human capacity for long term separation from Earth, other beings, family.
  - Isolation.
  - Boredom.
  - Need for natural Earth-like environments.

# Why Mercury and Saturn?

- **At Mercury:**
  - **Permanently shadowed craters.**
  - **Water ice at the northern polar craters.**
- **At Saturn: Titan.**
  - **Cryogenic surface and hydrocarbon (methane, ethane) oceans.**
  - **Potential for subsurface water ocean.**
- **At Saturn: Mimas, Enceladus, Iapetus.**
  - **Cryogenic surface water ice and regolith.**
  - **Potential for subsurface water oceans, at Endeladus, etc.**

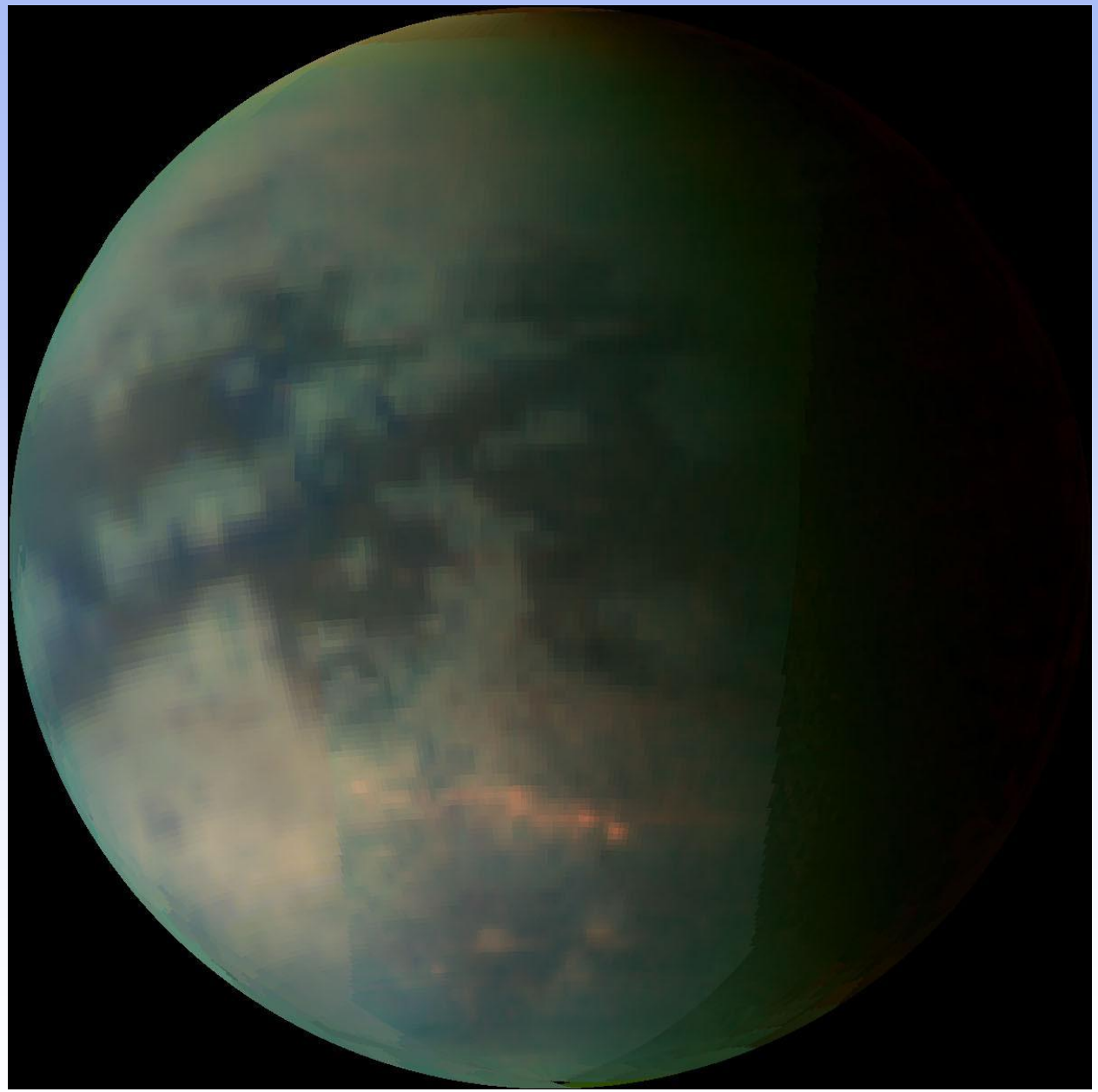
# Permanently Shadowed Craters



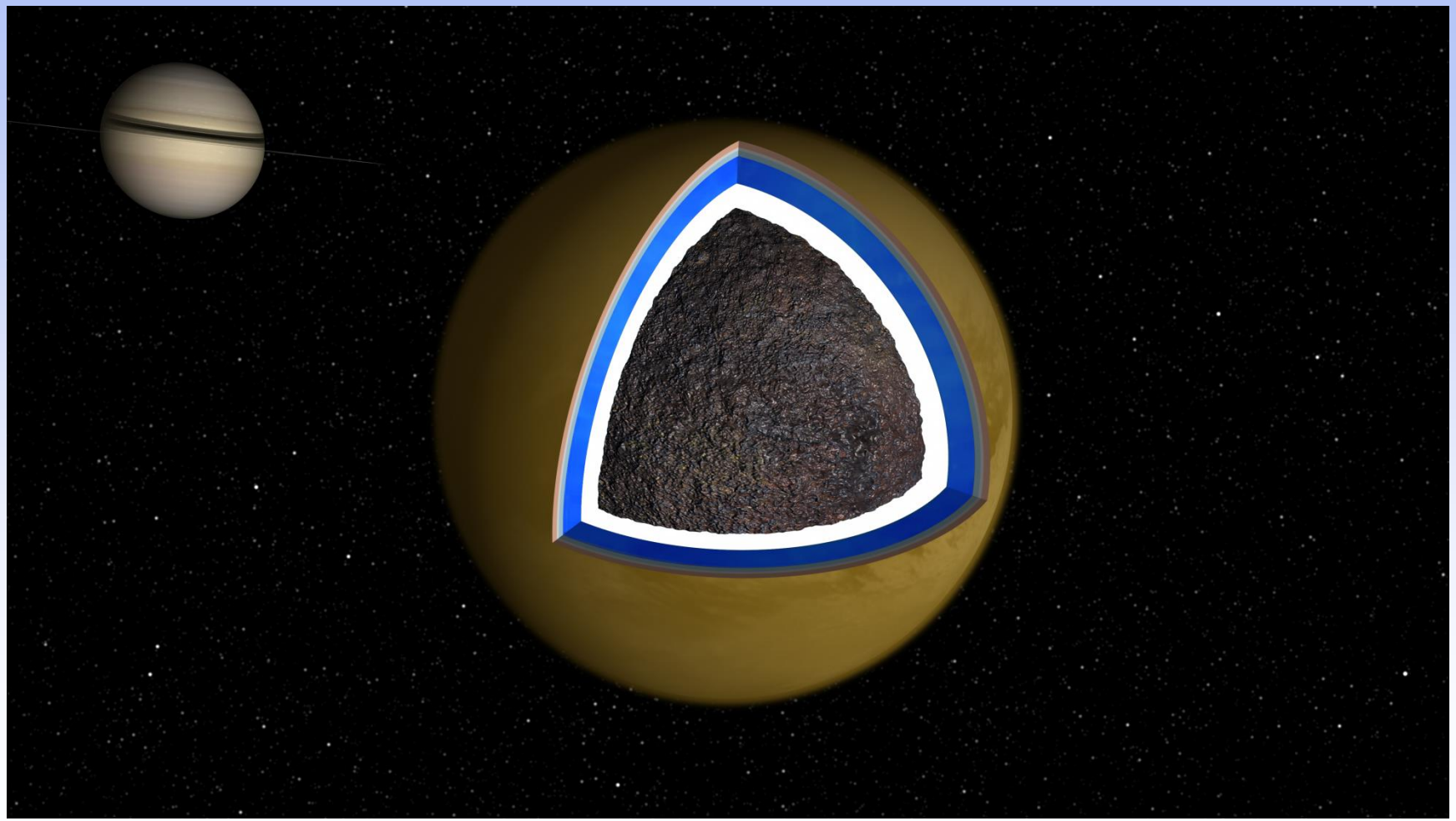

**MESSENGER / JHU / Lawrence, APL.,11-2012**

# Cryogenic issues for permanently shadowed craters

- At Mercury:
  - Permanently shadowed craters.
  - Water ice at the northern polar craters.
- Water ice capturing tools.
- Liquefaction.
- Purification and elimination of salts.
- Creation of oxygen and hydrogen.
  - Propellants.
  - Breathing gases.
- Gravity level is 0.38 G.
- Processes may not require assistance of artificial gravity.



# Cassini Spacecraft Finds Ocean May Exist Beneath Titan's Crust (Gravity Measurements)



# Cryogenic moon surface issues (1 of 3)

- **At Titan:**
  - **Cryogenic surface and hydrocarbon (methane, ethane) oceans.**
  - **Potential for subsurface water ocean.**
- **Safety on icy surface.**
- **Heating of surface ices by human activities.**
- **Motion of landers and “permanent bases” of moving icy surfaces.**
- **Gravity level is 0.138 G.**
- **Processes may not require assistance of artificial gravity.**

# Cryogenic moon surface issues (2 of 3)

- At Titan.
- Deep drilling to water ocean.
- Heavy machines required for large scale drilling, resource recovery, etc.
- Resupply of human outposts, spare parts, propellants, etc.

# Cryogenic moon surface issues (3 of 3)

- At icy moons: Mimas, Endeladus, Iapetus, etc.
- On the surface, water ice mixed with regolith.
- Less intensive, smaller scale drilling, resource recovery, etc., than at Titan.
- Resupply of human outposts, spare parts, propellants, etc.
- Issues with gravity levels must be address – is oxygen and hydrogen ISRU feasible in very low gravity?
- Enceladus gravity = $1.2 \times 10^{-2}$ G.
- Processing in low gravity may be a serious issue.
- Is an artificial gravity "space base" required?

EXPANDED
CAPABILITY
SPACE STATION

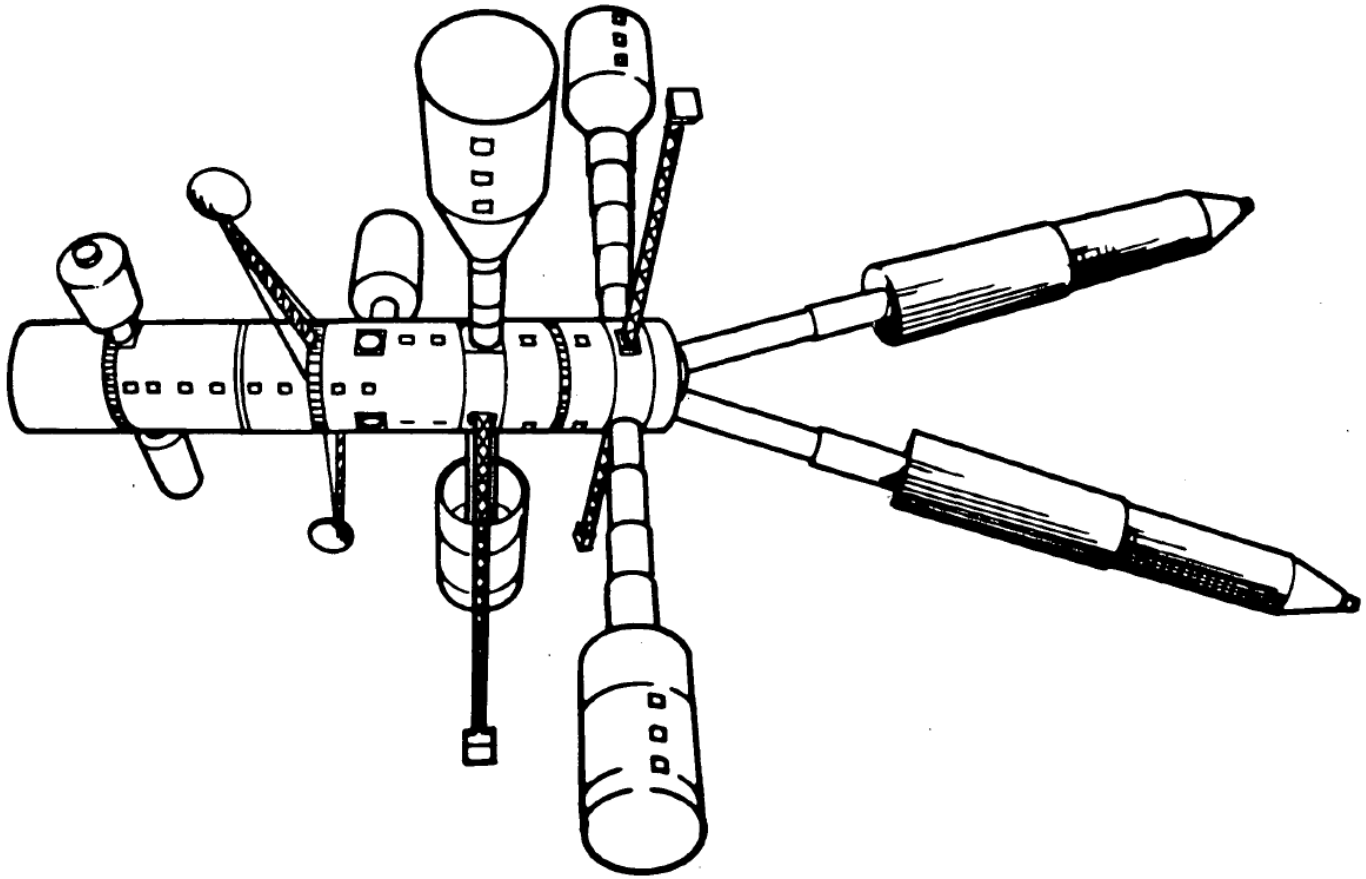
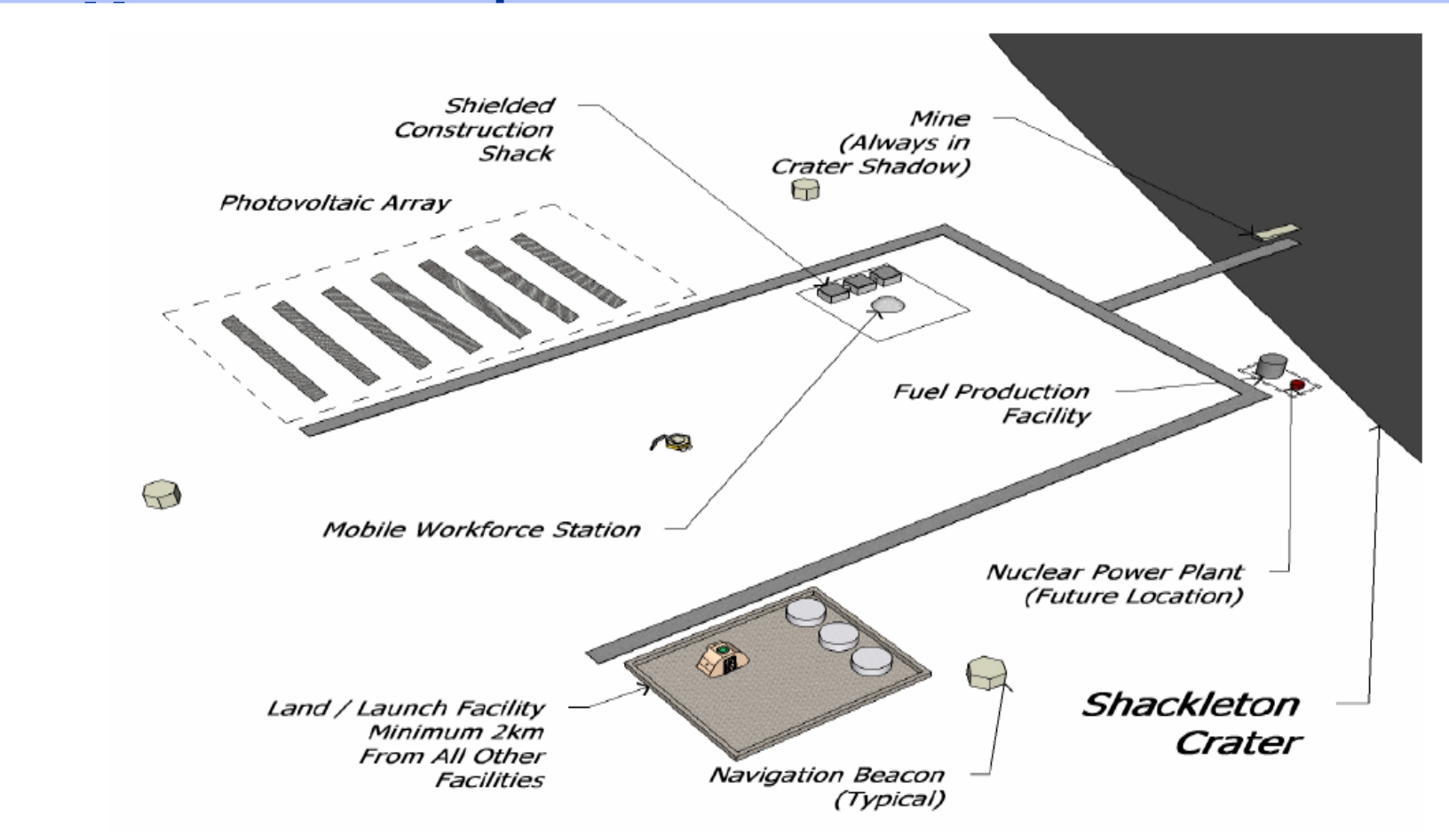


Figure 1-3. Preferred Space Base Configuration

# Mercury Crater Base, Using Lunar Base Example



# Mission analyses

- Mission delta-V values (km/s):
  - Earth departure 5.2
  - Mercury arrival 10.9
  - Mercury departure 8.7
  - Earth arrival direct capsule entry
  - Worst case, highest delta-V mission selected.
- Stay time, Mercury = 40 days.
- Flight time, round trip = 585 days.

Manning, L., AIAA 67-28.

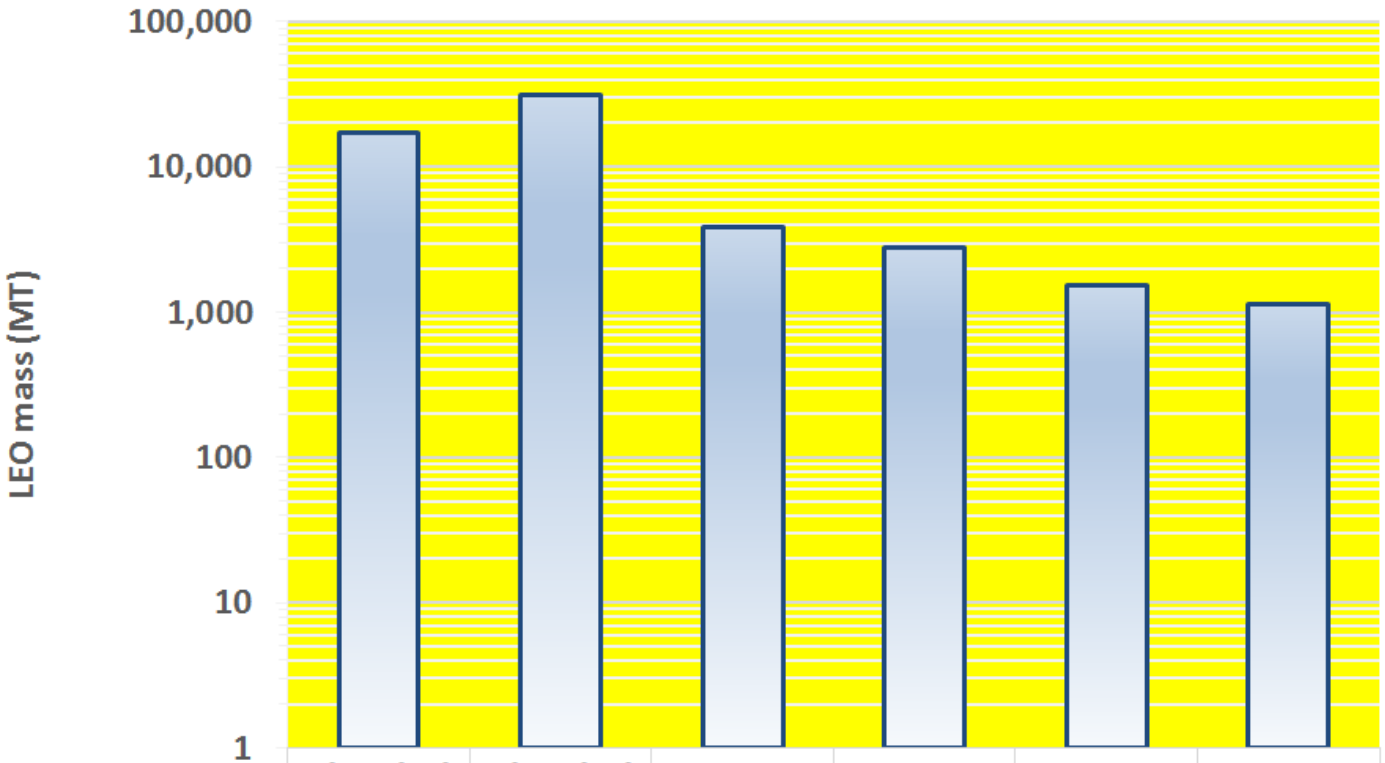
# Propulsion analyses

- Chemical propulsion, interplanetary.
- Vehicle specific impulse = 450 seconds.
- Mass scaling, dry mass.
  - M,dry = A + B M,p (MT)
  - A = 0 MT.
  - B parameter is varied: 0.03 and 0.05.
  - Three (3) stages were used.
- Round-trip (human) payload mass = 4.4 MT, capsule.
- One-way cargo = 140 MT.

# Propulsion analyses

- Nuclear thermal propulsion, interplanetary.
- Vehicle specific impulse = 800 and 850 seconds.
- Mass scaling, dry mass.
  - M,dry = A + B M,p (MT)
  - A = 0 MT.
  - B parameter is 0.33.
  - Six (6) stages were used in the vehicle design.
- Round-trip (human) payload mass = 4.4 MT, capsule.
- One-way cargo = 140 MT.

# Mission Analyses: Human Mercury Missions – Mercury ISRU: B = 0.33

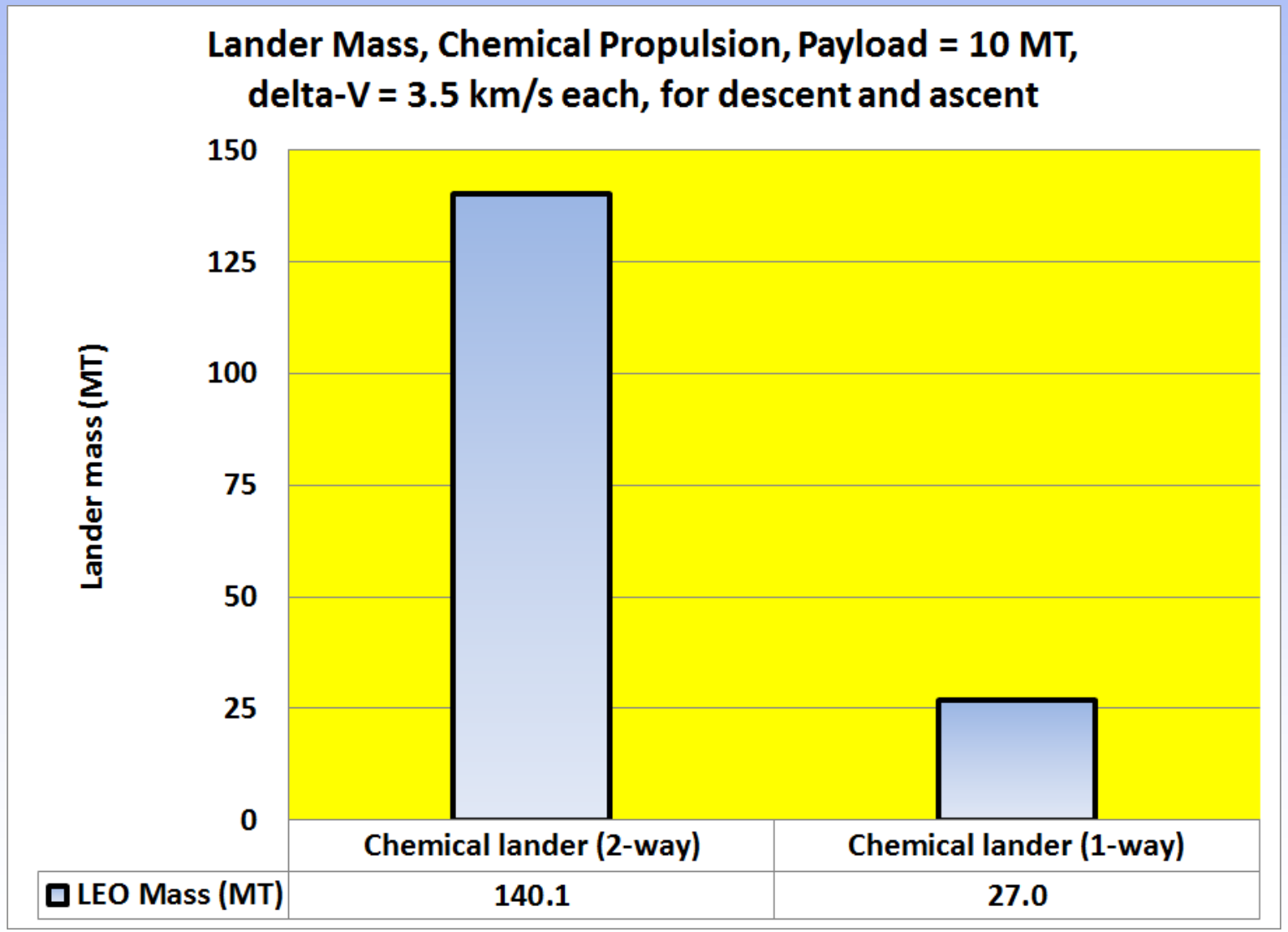



| | Chemical -1 | Chemical -2 | NTP-1 | NTP-2 | NTP-1, ISRU | NTP-2, ISRU |
|---|---|---|---|---|---|---|
| LEO Mass (MT) | 17,146 | 31,228 | 3,892 | 2,793 | 1,517 | 1,136 |

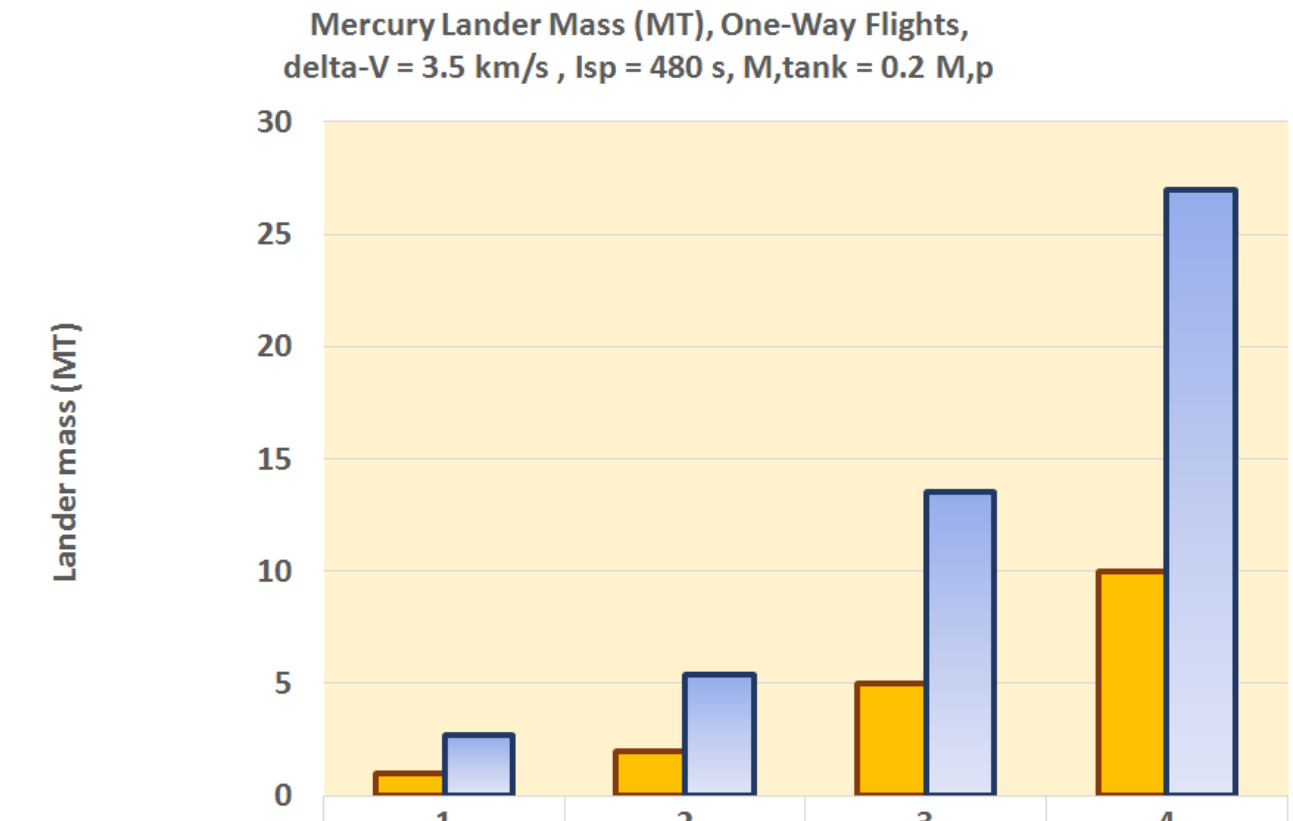
# Propulsion analyses, Mercury

- Chemical propulsion, Landers.
- Vehicle specific impulse = 480 seconds.
- Mass scaling, dry mass.
  - M,dry = A + B M,p (MT)
  - A = 0 MT.
  - B parameter is varied: 0.20 and 0.40.
  - One (1) stage was used.
- Round-trip cargo payload mass = 1 to 10 MT.
- One-way cargo mass = 1 to 10 MT.

# Mercury Lander Mass

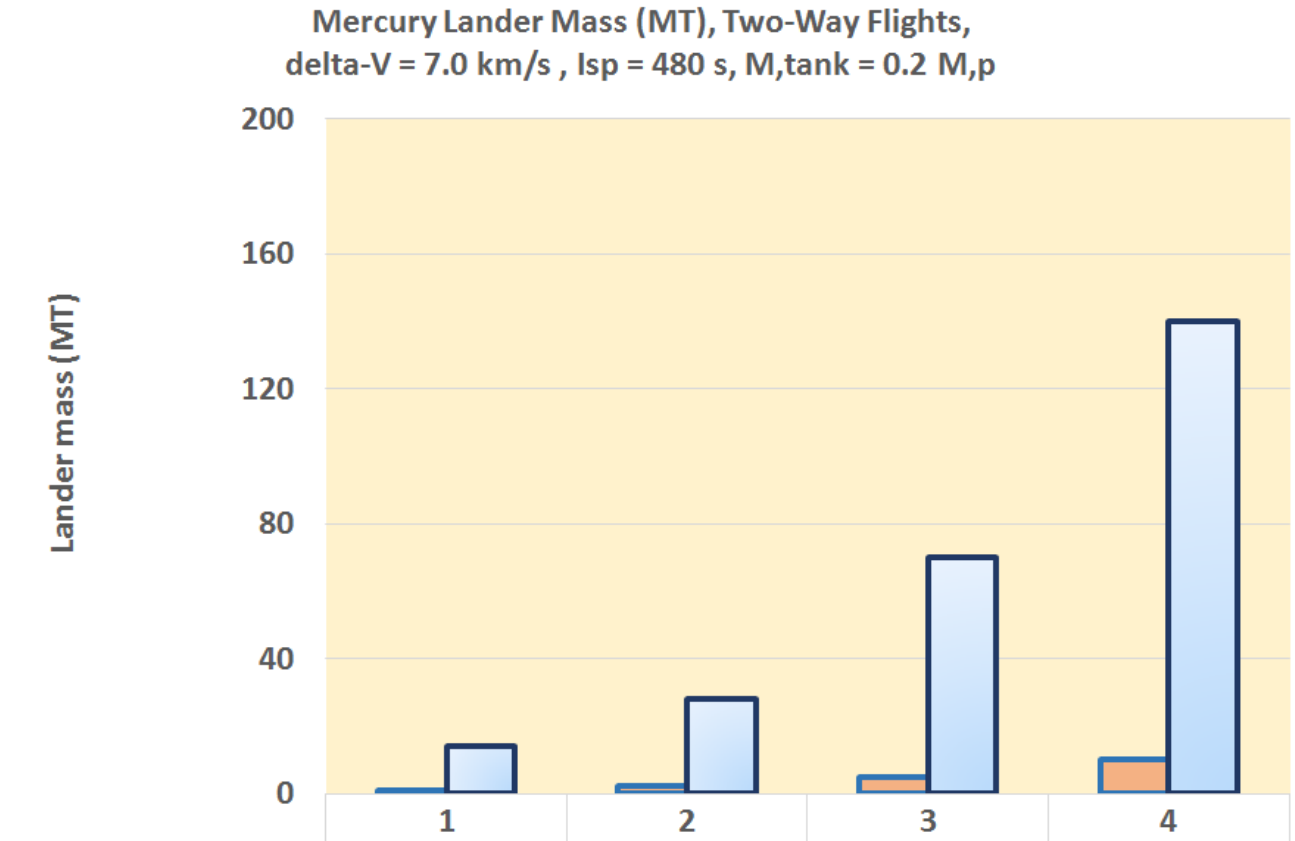


# Mercury Landers, One Way




| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Payload mass (MT) | 1 | 2 | 5 | 10 |
| Lander mass (MT) | 2.7 | 5.4 | 13.5 | 27.0 |

# Mercury Landers, Round Trip




| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Payload mass (MT) | 1 | 2 | 5 | 10 |
| Lander mass (MT) | 14.0 | 28.0 | 70.1 | 140.1 |

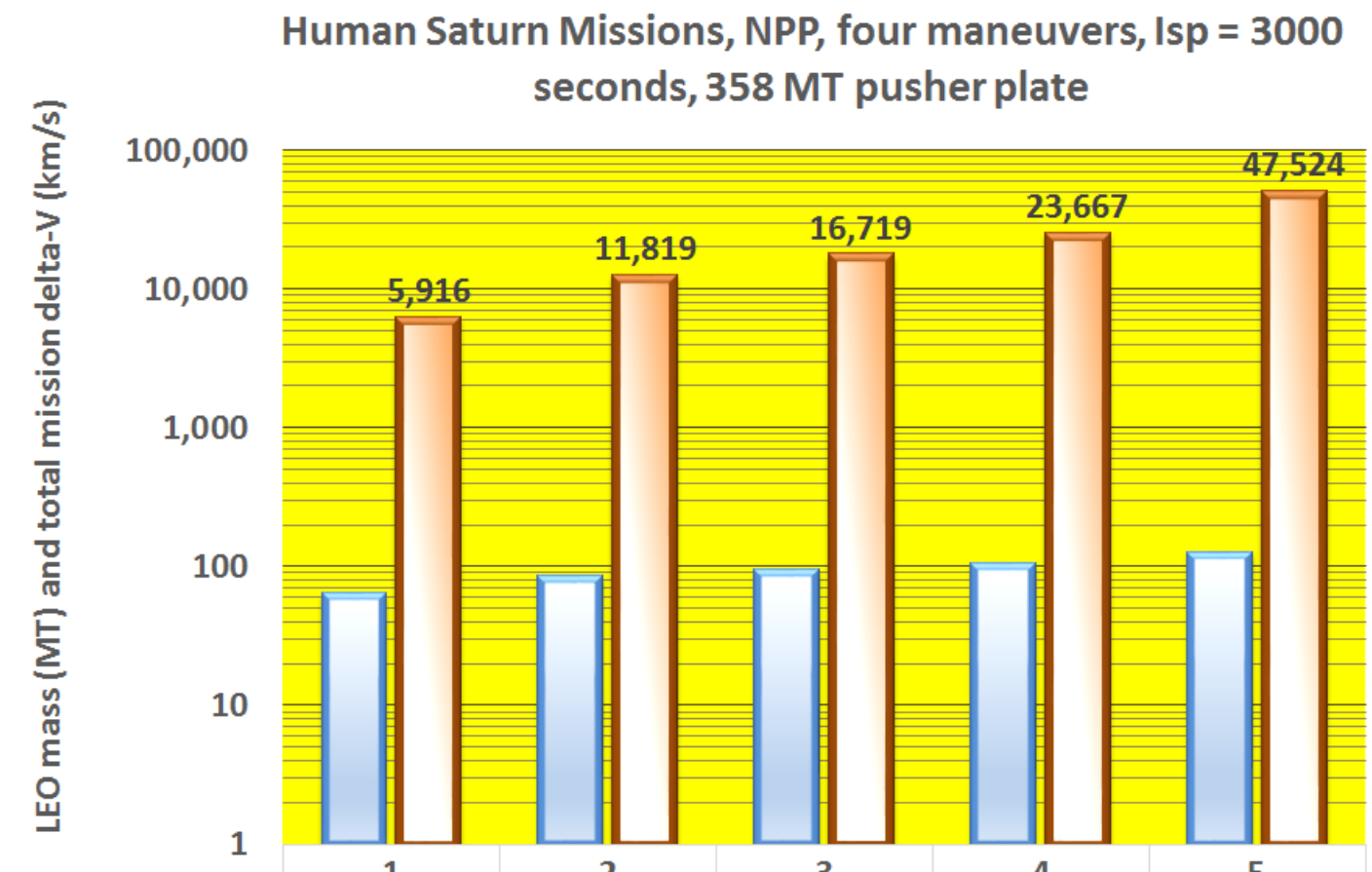
# Propulsion analyses, Saturn

- Nuclear pulse propulsion, interplanetary.
- Vehicle specific impulse = 3000 seconds.
- Mass scaling, dry mass.
  - M,dry = A + B M,p (MT)
  - A = 358 MT.
  - B parameter is varied: 0.01 and 0.10.
- Payload mass = 302 MT.

Nuclear Pulse Propulsion Mass Scaling and Mission Design -

# Mission Design – Saturn

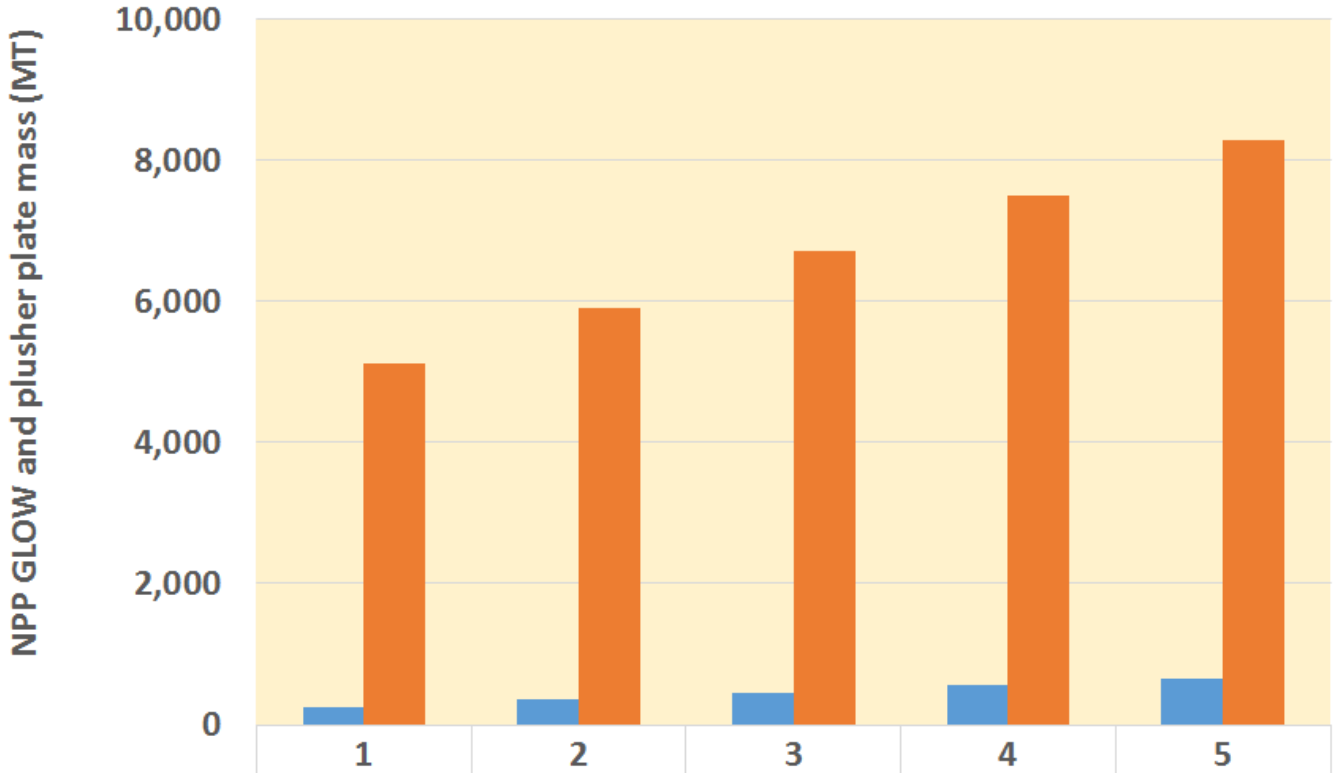
## (358 MT pusher plate, Ehricke, et al., 0.01 Mp variable mass)




| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Delta-V (km/s) | 60 | 80 | 90 | 100 | 120 |
| LEO mass (MT) | 5,916 | 11,819 | 16,719 | 23,667 | 47,524 |

# Mission Design – Saturn

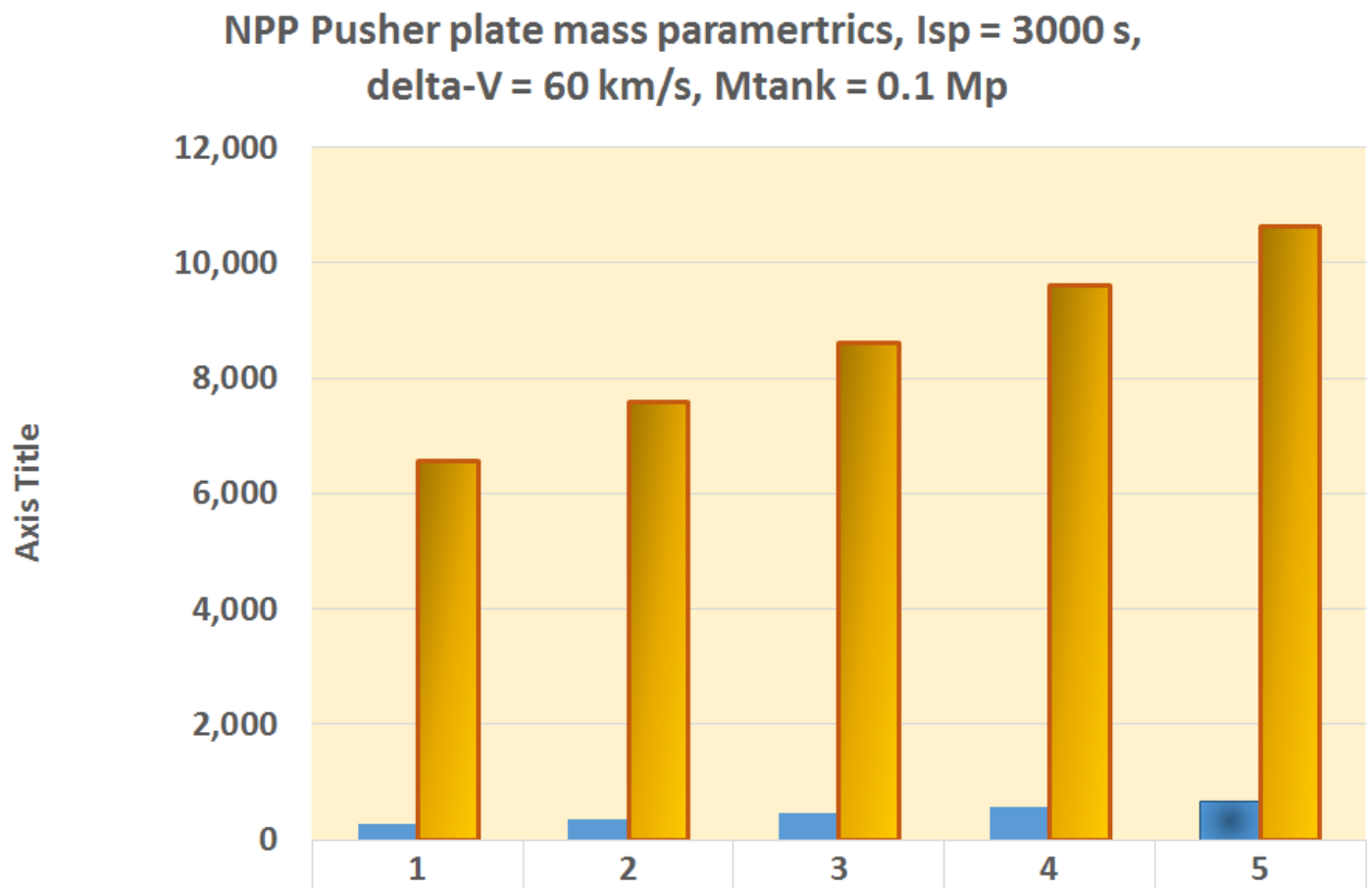
## (358 MT pusher plate, parametrics, Ehricke, et al., 0.01 Mp variable mass)




| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| M, plate (MT) | 258 | 358 | 458 | 558 | 658 |
| NPP GLOW (MT) | 5,127.4 | 5,916.2 | 6,705.1 | 7,494.0 | 8,282.8 |

# Mission Design – Saturn

## (358 MT pusher plate, Ehricke, et al,parametrics, 0.10 Mp variable mass)

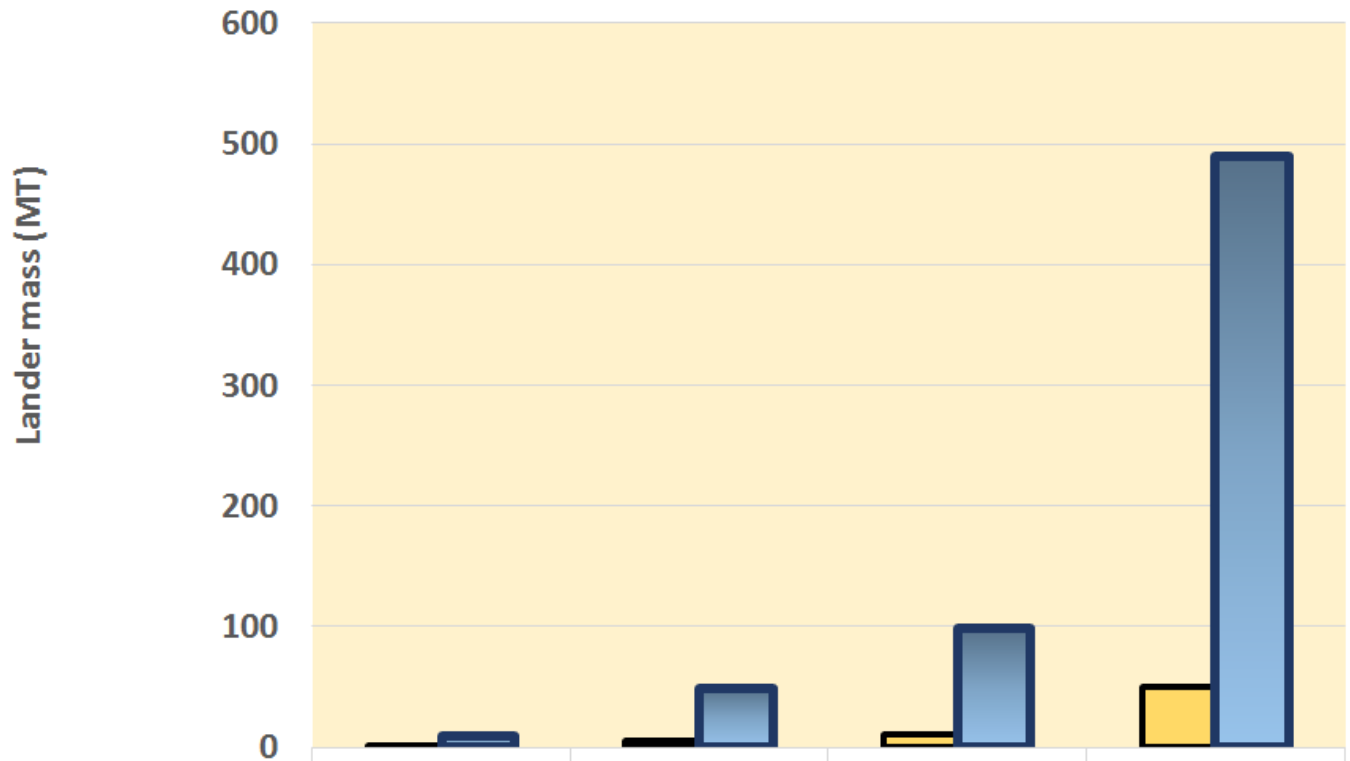



| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| M, plate (MT) | 258 | 358 | 458 | 558 | 658 |
| NPP GLOW (MT) | 6573.7 | 7,585.0 | 8,596.4 | 9,607.8 | 10,619.1 |

# Propulsion analyses, Saturn's Moons

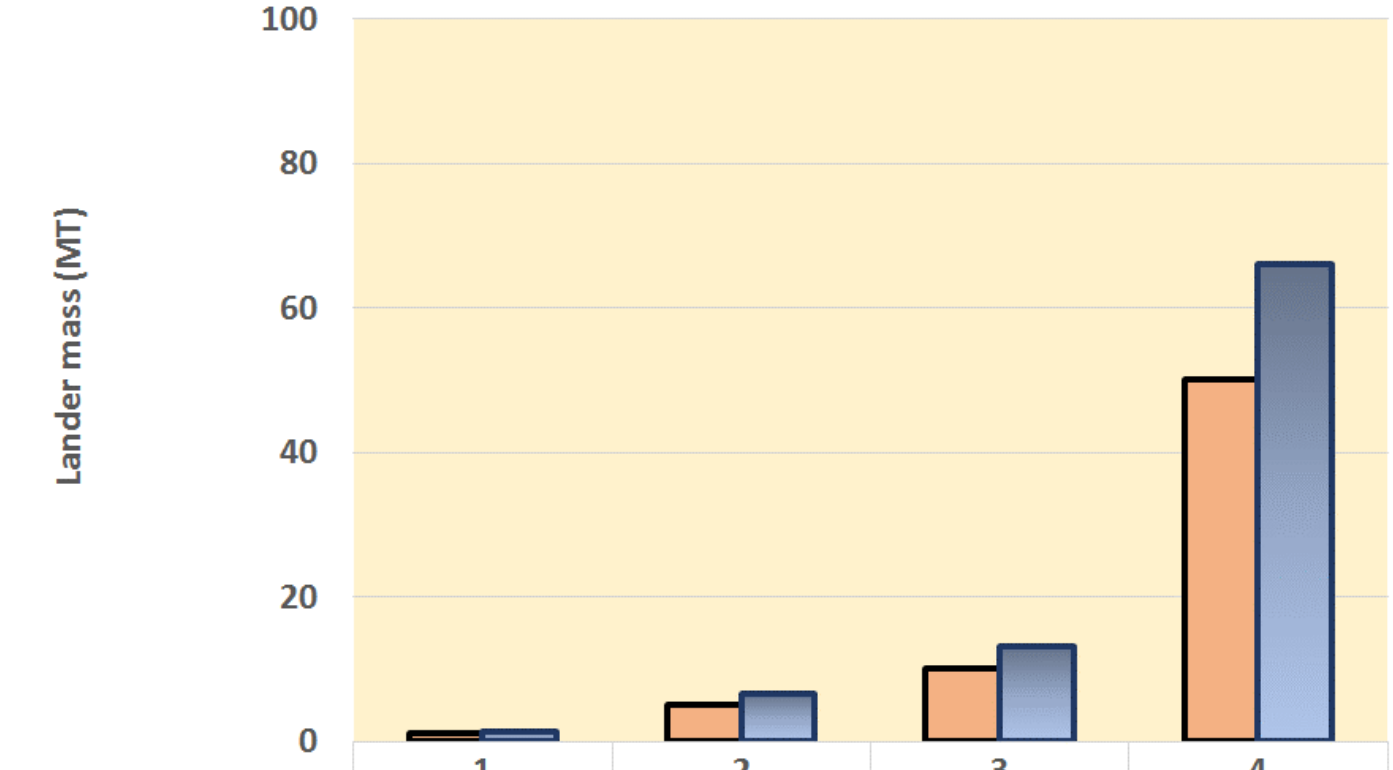
- Chemical propulsion, Landers.
- Vehicle specific impulse = 480 seconds.
- Mass scaling, dry mass.
  - M,dry = A + B M,p (MT)
  - A = 0 MT.
  - B parameter is varied: 0.20 and 0.40.
  - One (1) stage was used.
- Round-trip cargo payload mass = 1 to 50 MT.

# Saturn Moon Landers, Round Trip: Titan



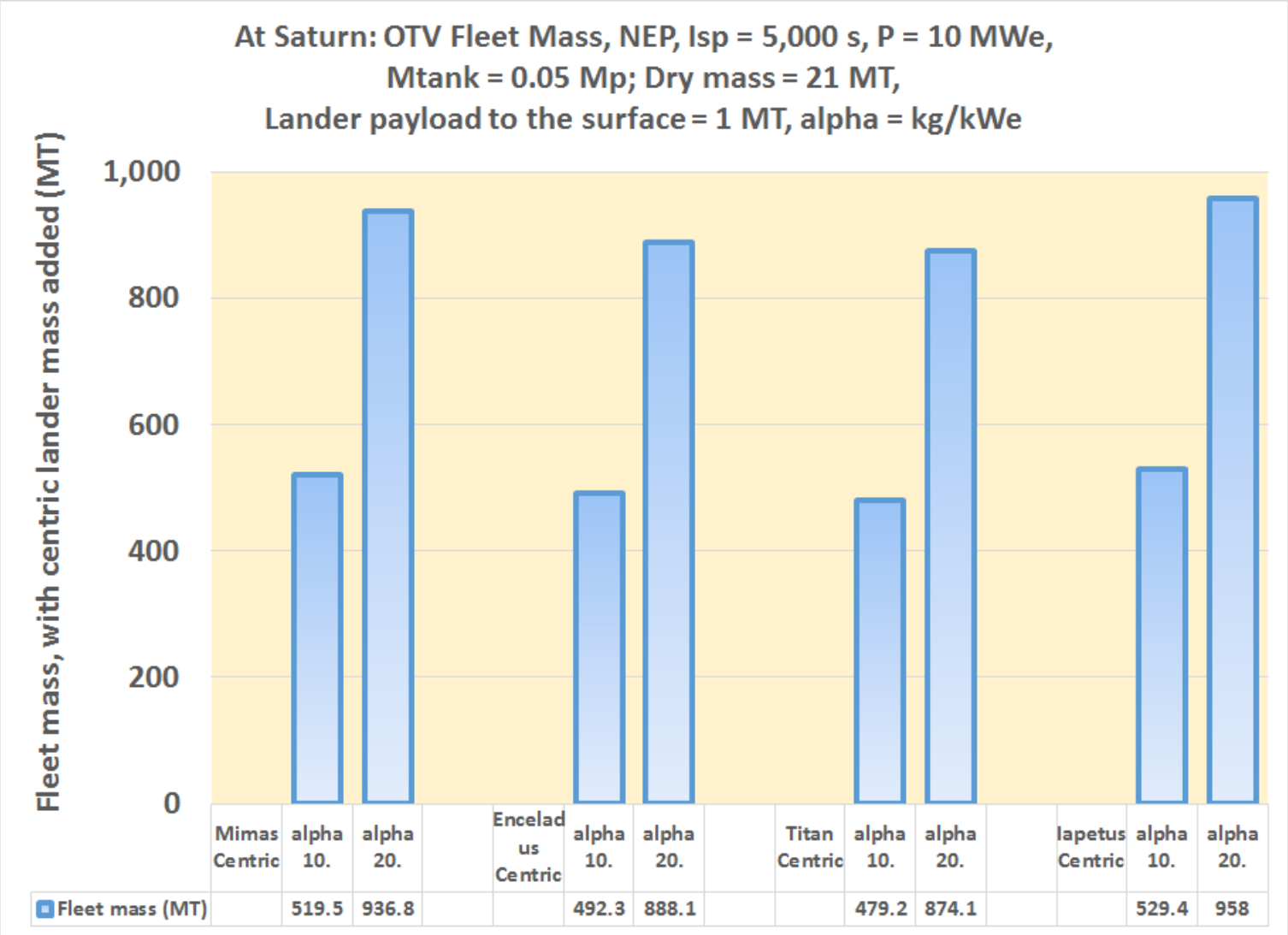

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Payload mass (MT) | 1 | 5 | 10 | 50 |
| Lander mass (MT) | 9.8 | 49.0 | 98.0 | 490.2 |

# Saturn Moon Landers, Round Trip: Enceladus




| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Payload mass (MT) | 1 | 5 | 10 | 50 |
| Lander mass (MT) | 1.3 | 6.6 | 13.2 | 66.1 |

# Saturn OTV and Lander Fleet Sizing



# Saturn OTV and Lander Fleet Sizing

| Titan Centric: | Mimas | Enceladus | Titan | Iapetus | Total OTV fleet mass (MT), or delta-V (km/s) |
|---|---|---|---|---|---|
| Estimated delta-V of landers (km/s), R-T. | 0.4 | 0.6 | 6.34 | 1.4 | |
| Estimated mass of landers (MT). | 1.24 | 1.3 | 9.8 | 1.7 | 14.04 |
| Estimated delta-V of OTVs (km/s) R-T. | 17.5 | 14.1 | 0 | 5.7 | 37.3 |
| Estimated mass of OTVs, alpha = 10 (MT). | 177.1 | 164.5 | 0 | 137.6 | 479.2 |
| Estimated mass of OTVs, alpha = 20 (MT). | 323.1 | 300 | 0 | 251 | 874.1 |

# Concluding Remarks (1/3)

- A wide range of space exploration technologies have been assessed in many studies from the 1950's to today.
- Water resources are available at Mercury in PSC.
- Water, deuterium, helium 3 are available at Saturn.
- The LEO masses for the human round trip Mercury missions was reduced by an order of magnitude, from 31,300 to 17,200 MT to 3,900 to 2,800 MT, using nuclear thermal propulsion over chemical oxygen /hydrogen propulsion systems.
- Using ISRU at Mercury would further benefit a range of such missions (refueling from water resources, etc.).
- ISRU (producing hydrogen) can reduce the Mercury round trip mission mass to 1,520 and 1,140 MT, respectively.

# Concluding Remarks (2/3)

- Lander (ascent/descent) vehicles for Mercury were also assessed. Each carried a 1 to 10 MT payload.
- For a 10 MT payload, the mass of the lander vehicles for Mercury was 140.1 MT for the round trip lander and 27 MT for a one-way deliver lander to the surface.
- With ISRU, five landers could be delivered to Mercury's surface rather than one.
- Human Saturn missions were assessed with NPP.
- The LEO masses for the human round trip Saturn missions was reduced by an order of magnitude, from 48,000 to 6,000 MT, using ISRU for refueling at Saturn.
- The NPP pusher plate was parametrically assessed from 258 to 658 MT.
- With the 658 MT plate, the NPP LEO initial mass was a maximum of approximately 8,300 to 10,600 MT.

# Concluding Remarks (3/3)

- An OTV and lander fleet, exploring Saturn's moons was assessed.
- A Titan-centric OTV fleet allowed the lowest fleet mass with 480 MT to 875 MT. Enceladus was a close second with 493 to 890 MT.
- In an optimistic future, lunar exploration will lead to base construction and, with time, lead to extensive lunar industrial investments, with many Earth benefits.
- Mercury and Saturn moon bases will benefit from the lunar base experiences.
- Lunar bases would be excellent test sites for planetary missions and potentially construction sites for enormous and powerful interplanetary space vehicles.
- Krafft Ehricke's vision of a polyglobal civilization would lead to endless new innovations and discoveries.