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Nuclear Electric Propulsion for Outer Planet Science Missions
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Accelerating Space Science with Nuclear Technology: The Tempe Workshop

- Collection of Space Nuclear Propulsion and Power Technologists

  &

- Space Science Principal Investigators

  discussing

- Present state and possible future capabilities provided by nuclear tech
- Needs and desires of the space science community

"Accelerating Space Science with Nuclear Technology: The Tempe Workshop", T. Reuter, R. Myers, P. Christensen, L. Dudzinski, and K. Polzin; Institute for Space Science and Development; December 2023; https://i-ssd.org.

Tempe Workshop Summary

NEP Technologists...

- Can deliver a very large payload at the destination & provide orders of mag more power than RTG systems

Space Scientists...

- That’s great, but not what we want
- ***Wants***: Faster Trip Times, More Mission Opportunities, More Power (for comms or high-power instruments)
- Don’t want excess mass for more instruments, but, could use it for other purposes (rad shielding or additional prop for in-system maneuvers)

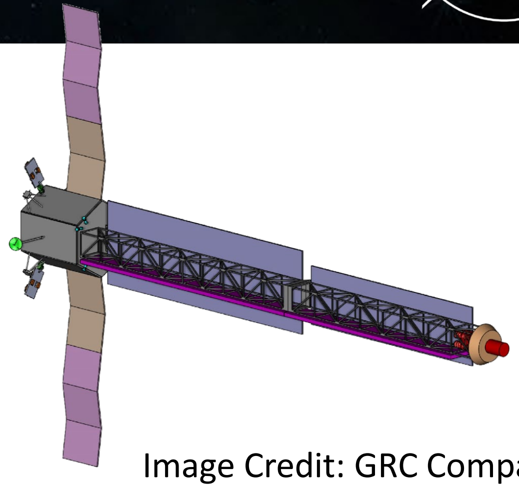
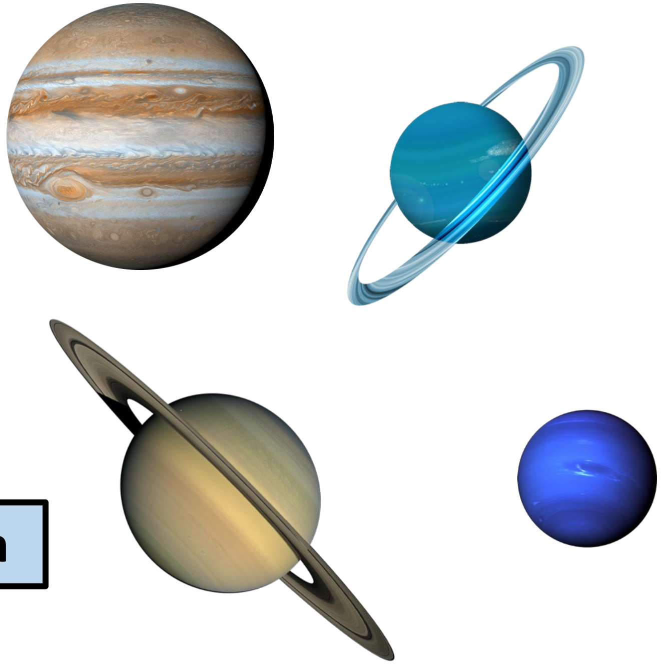


Image Credit: GRC Compass Lab



Very different from how the EP community has been approaching the problem

Nuclear Electric Propulsion (NEP) for Outer Planet Science Missions

- NEP enables constant-power electric propulsion (EP) throughout the solar system
- This paper shows NEP expands possibilities for mission design
  - Launch window flexibility, direct or only Earth-gravity-assist (EGA) trajectories to gas giants
  - Reduced arrival V_∞ compared to a ballistic trajectory
    - Small ΔV chemical orbit insertion burn –or –
    - Capture into Saturn orbit by an unpowered Titan flyby
  - EP-powered moon tour design (maneuverability in the planetary system)
  - EP-powered departure from outer planet sphere of influence (SOI) – enabling sample return mission

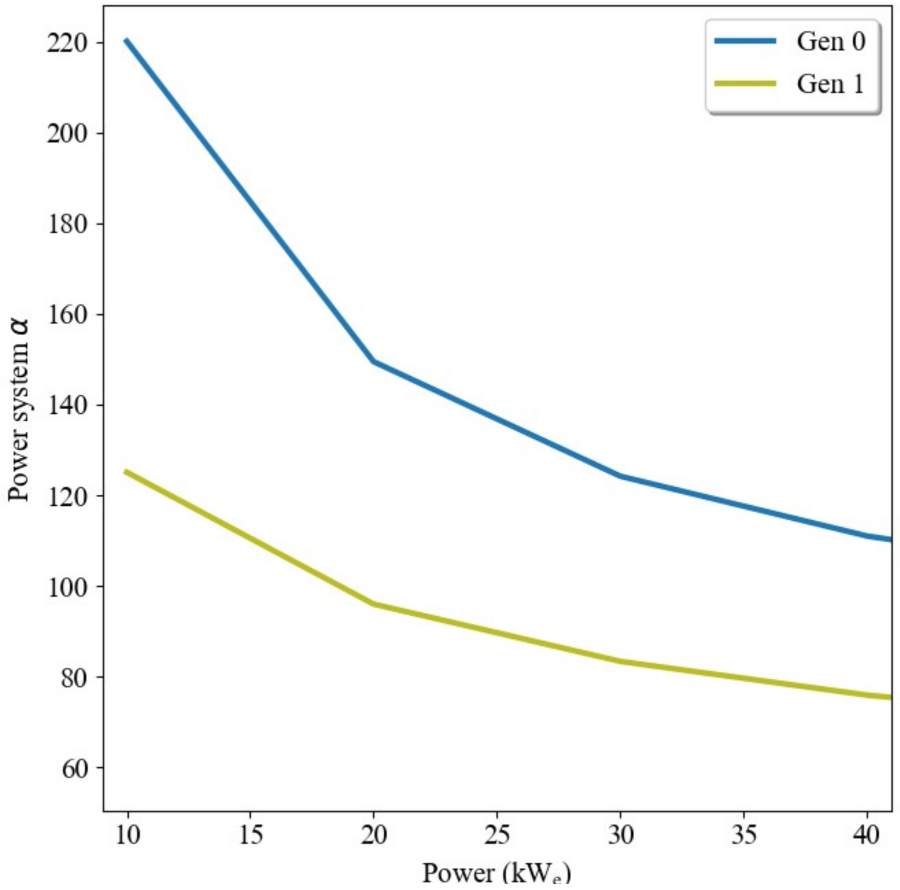
In the Sphere of Influence (SOI) of a Gas Giant

- Nuclear power source can support payloads and communication systems with kW's of electric power
  - Enables order of magnitude higher data rates & data volume returns
- kW-level EP available for maneuvering within the SOI
  - Enables moon tours and orbital adjustments

NEP System Performance Assumption

- NASA's Fission Surface Power (FSP) project is developing space nuclear power system technology
  - Gen 0 → FSP-derived NEP system
- NASA's Space Nuclear Propulsion (SNP) project is maturing technologies for improved performance over Gen 0 NEP systems
  - Gen 1 → Incorporates technology maturation to yield step-change improvement in NEP performance beyond the Gen 0 system

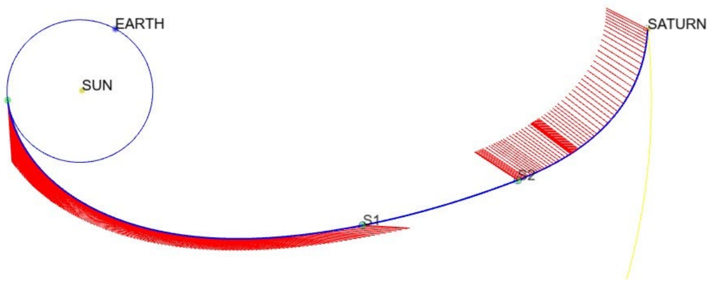
Power System specific mass (kg/kW$_e$) as a function of generated NEP power



Saturn Mission Examples of NEP Performance

1. Direct Trajectory to Saturn

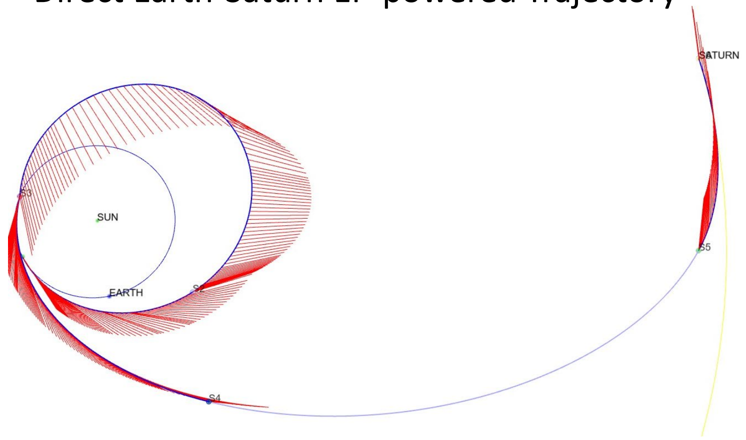
- Increased launch window flexibility
- No planetary flybys
- Reduced time of flight (TOF) to Saturn in some cases compared to trajectories with an Earth flyby and to chemical propulsion missions



Direct Earth-Saturn EP-powered Trajectory

2. Maximum Usable Mass to Enceladus

- Illustrates mass delivery capability
- Employs a longer-TOF trajectory
- Usable mass after arrival in the Saturn SOI available for:
  - Propellant (for in-system maneuvers)
  - Science instruments, landers, probes
  - Shielding



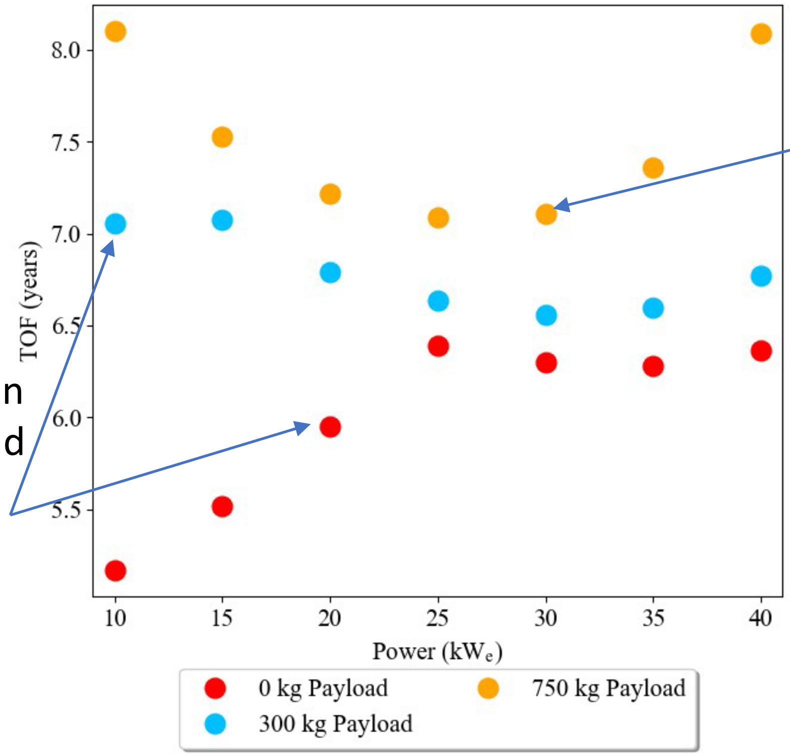
Earth-Saturn EP-powered Trajectory with an Earth Gravity Assist Maneuver

3. Enceladus Sample Return

- Large amount of propellant mass, 10’s kW_e NEP
- Long trip time but can close with a Gen 1 NEP system and high departure C_3

Direct transfer to Saturn with NEP increases mission planning flexibility

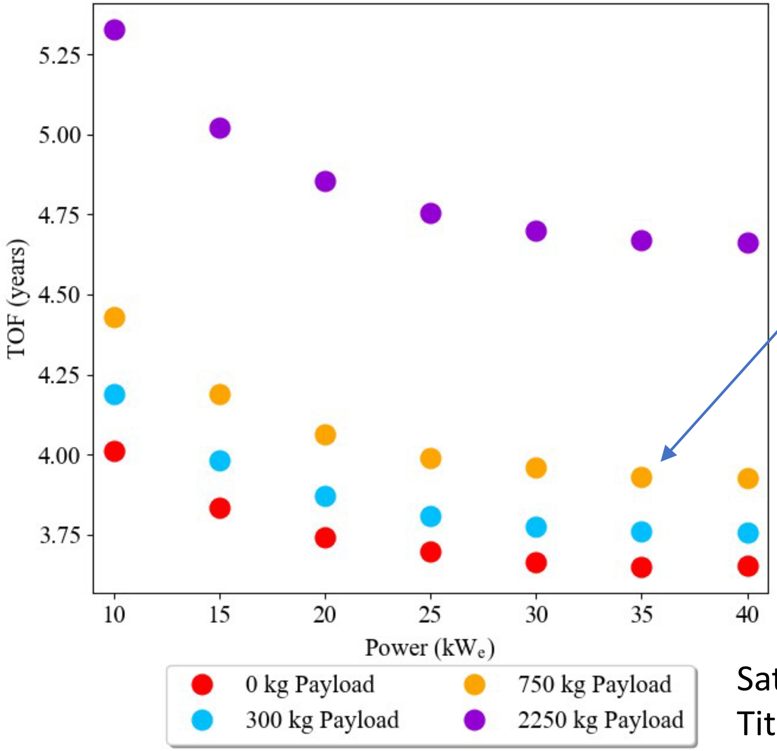
TOF to Saturn as a function of NEP System Power (Gen 1) with a Falcon Heavy Expendable (FHe) Launch



Performance comparable to Cassini, without gravity assist flybys of inner planets

Balance between C_3, S/C mass, and EP T/W yields discontinuity where E-S spiral path is much shorter

TOF to Saturn as a function of NEP System Power (Gen 1) with an SLS Launch



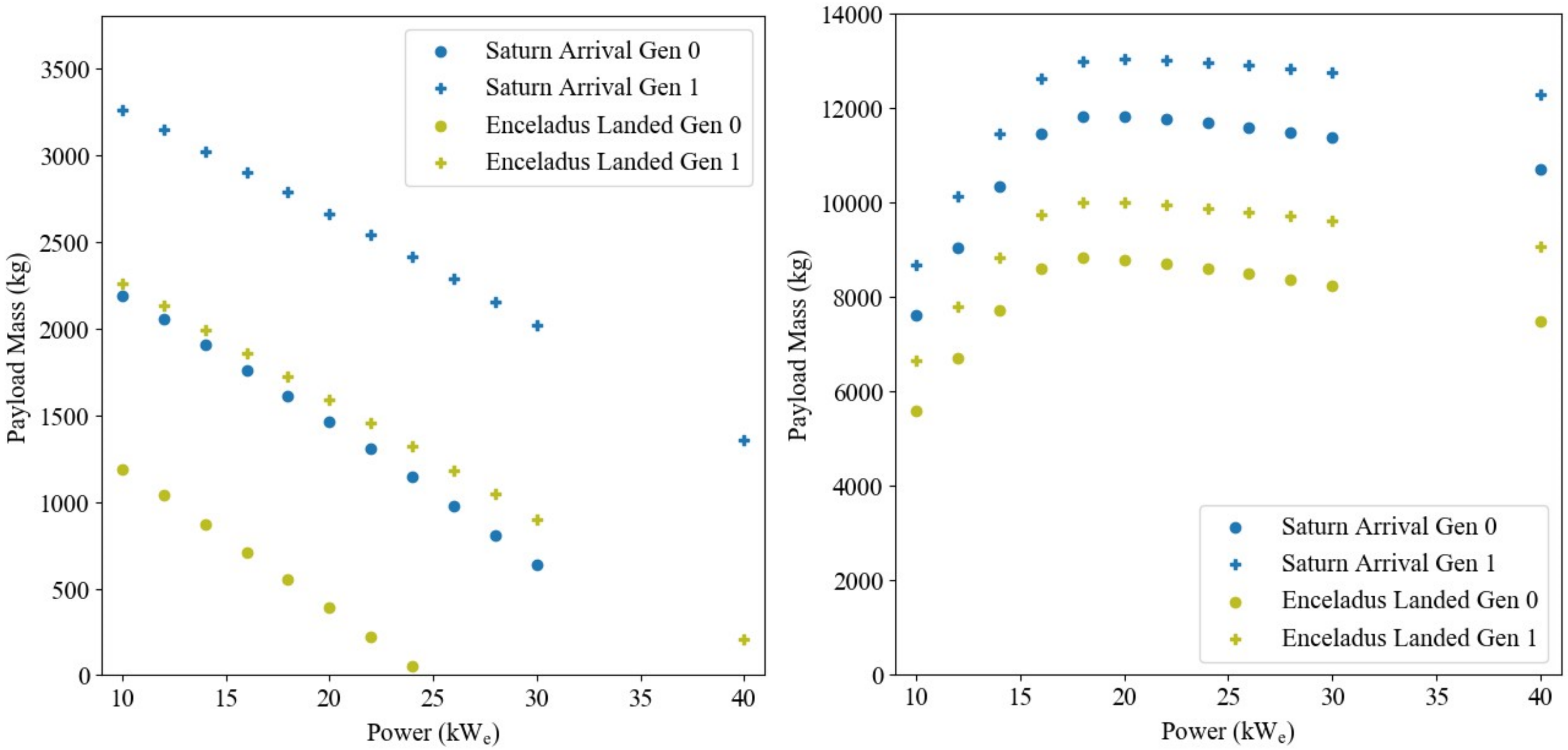
Payload comparable to Cassini, with much shorter TOF

Saturn orbit insertion by Titan flyby in all cases

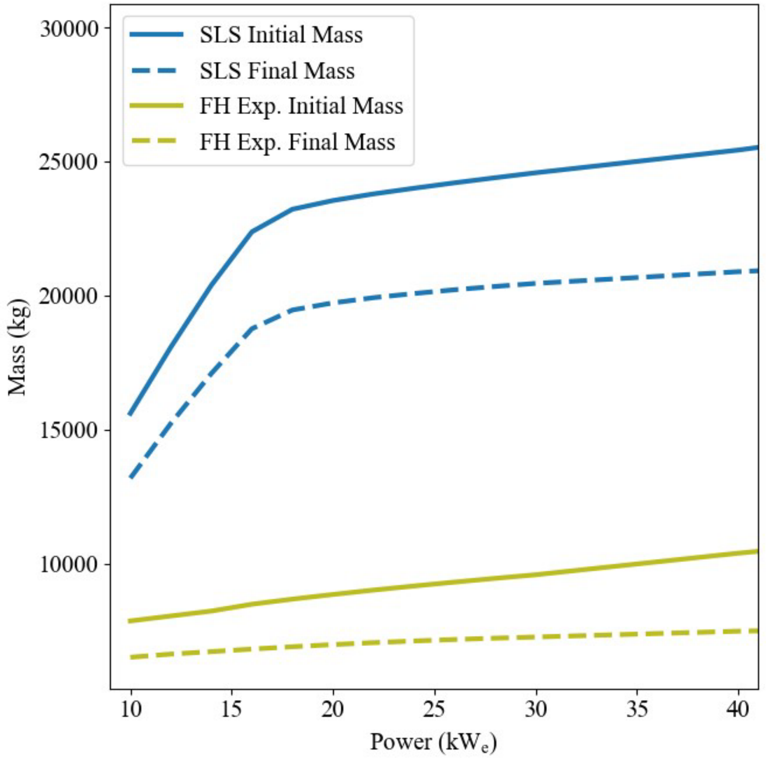
Yearly launch windows. No gravity assists.
Faster TOF to Saturn compared to Cassini (7 year TOF with a VVEJ trajectory).

High usable mass deliverable with EGA trajectory

Usable mass at Saturn SOI arrival and potentially landed on Enceladus for Gen 0 and Gen 1 NEP Launched by FHe (left) or SLS (right)



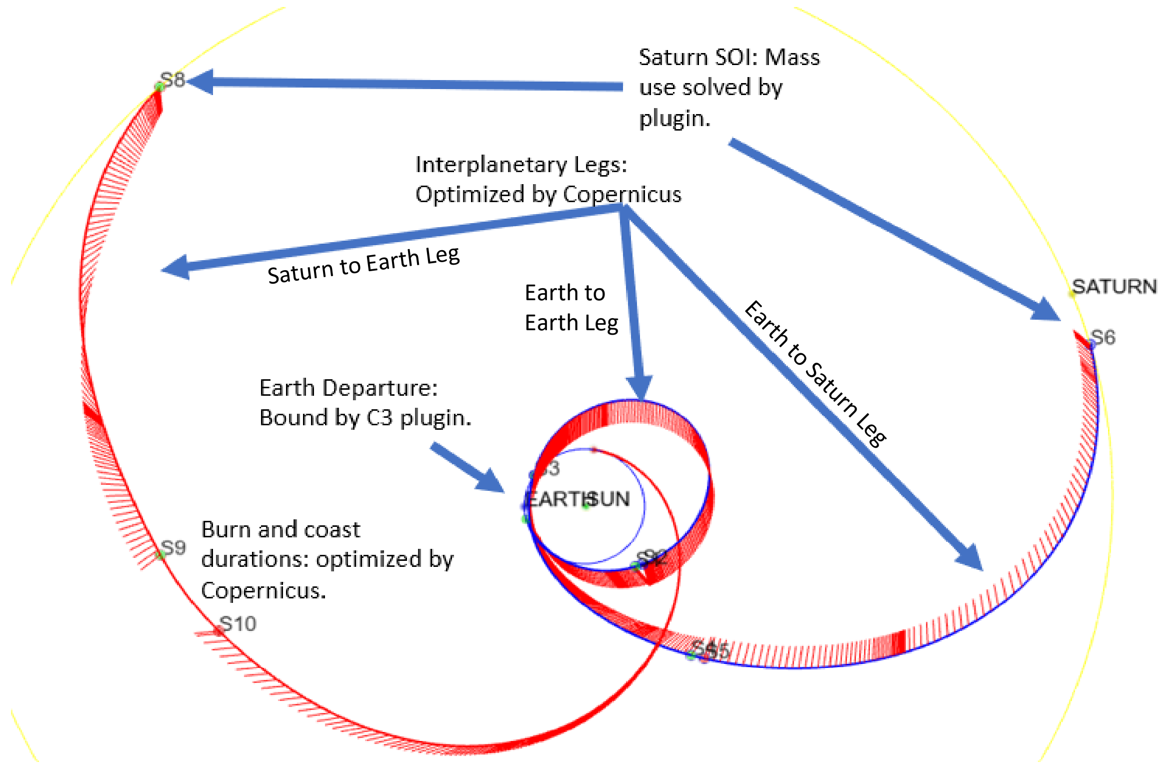
Spacecraft initial launch mass and final mass at Enceladus for Gen 1 NEP



Longer transfer TOF. EP-powered arrival minimizes propellant for Saturn orbit insertion. Enables large usable mass in-system. Significant prop budget for maneuvers or a lander.

Enceladus Sample Return Mission

Interplanetary Trajectory Concept



NEP system requires roughly 8000 kg Xe throughput and 17-20 years operating life to close Enceladus sample return. VERY CHALLENGING, BUT a Gen 1 NEP System Does Close

Mission ΔV Budget and Duration

Maneuver	ΔV Budget	Duration (Burn Length)
Earth to Saturn (series of 3-4 burns)	Launch C_3 = 44 km^2/s^2 EP to Saturn ~10 km/s	7.5 years (6.7 years)
Saturn orbit insertion (SOI)	0 m/s Titan flyby capture	
Moon Tour to Enceladus	380 - 1200 m/s EP Leveraging tour	2.7 - 5 years down
Enceladus Orbit Insertion/Departure	260 m/s chem for EOI and EOD	1-year orbital ops
Moon Tour Up	380 - 1200 m/s EP	2.7 - 5 years up
Saturn departure	0 m/s Titan flyby escape	
Saturn to Earth Burn 1	~ 8.5 km/sec EP	9.2 years (8.4 years)
Saturn to Earth Burn 2 (slow to Earth Arrival velocity)	~10 km/s EP (~ 12.5 km/s entry velocity [21])	
RCS for miscellaneous	75 m/s RCS for maintenance reserved to end of mission	
TOTAL	**EP ΔV of roughly 29 - 32 km/s** **Chemical bi-prop ΔV of 335 m/s**	**22.5 - 27 years**

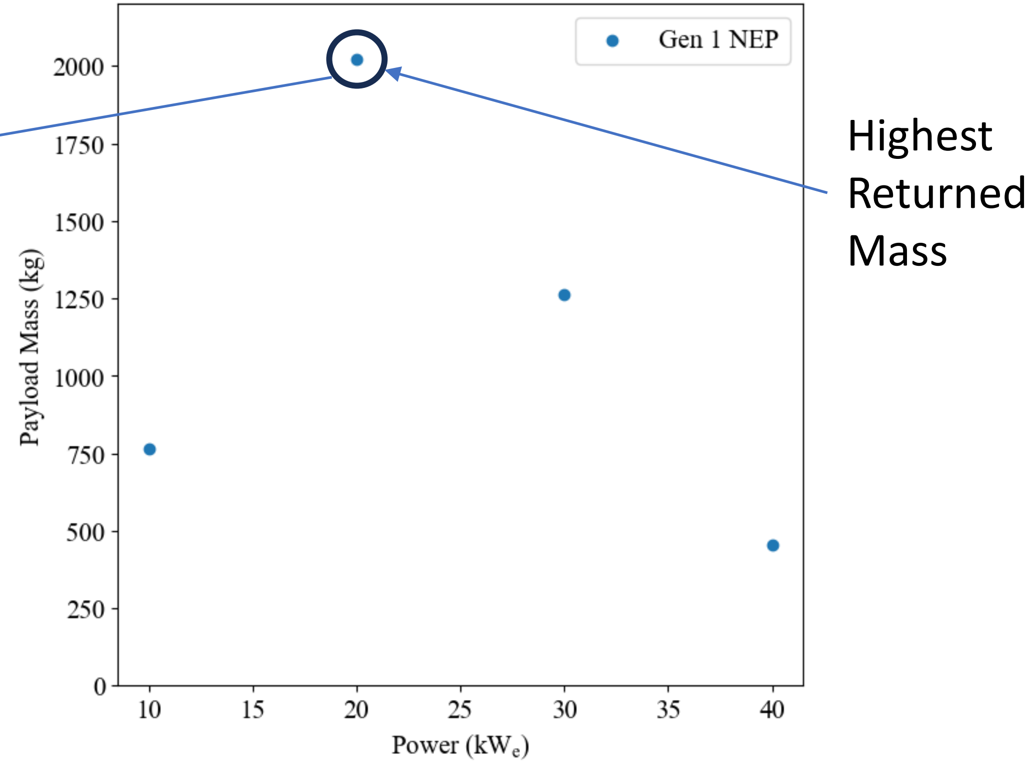
Mission closure by 20 kW$_e$ Generation 1 NEP system - with margin -

Spacecraft Summary

20 kW$_e$ Generation 1 NEP, SLS Launch

System	Description
Propulsion	20 kW$_e$, 4000 sec I_{sp} ion Thruster
Spacecraft Mass (without payload)	~16,100 kg Initial Mass (25% LV margin) ~4,700 kg Predicted Dry Mass (includes 15% MGA) 1000 kg RCS propellant 8400 kg EP propellant
Payload Example (2000 kg returned)	300 kg sample return entry vehicle 300 kg lander/collector 1,400 kg additional usable mass (27% additional dry mass margin)

Total usable mass returnable to Earth or allocable to propellant for shorter mission duration



Generation 1 NEP with heavy-lift launch and sufficient life closes sample return from Enceladus surface.

Conclusions

- Interaction with science community indicated interest in faster, more frequent missions and in maneuverability and communications power at destination
- Direct-to-Saturn mission analyses indicate potential for mission planning flexibility
  - Yearly launch windows
  - TOF comparable to or significantly less than previous missions
- Generation 1 NEP system with 17- to 20-year lifetime closes an Enceladus sample return
- Sample return mission concept represents an extreme example of a spacecraft that is highly-maneuverable upon reaching the Saturn system