



# RADIOISOTOPE POWER SYSTEMS PROGRAM

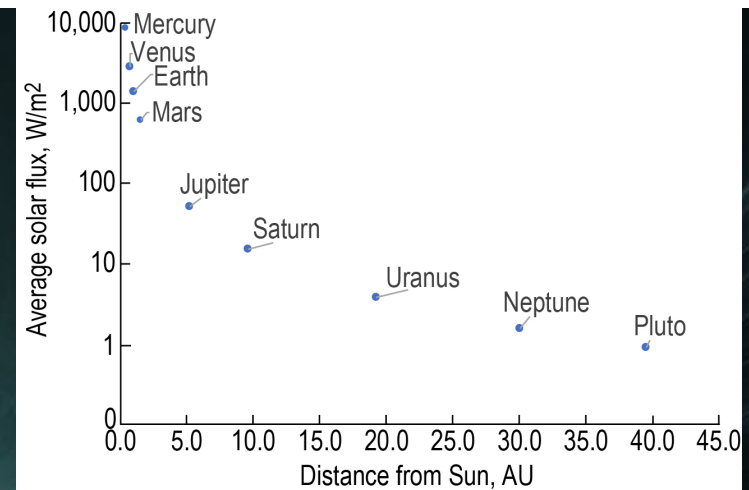
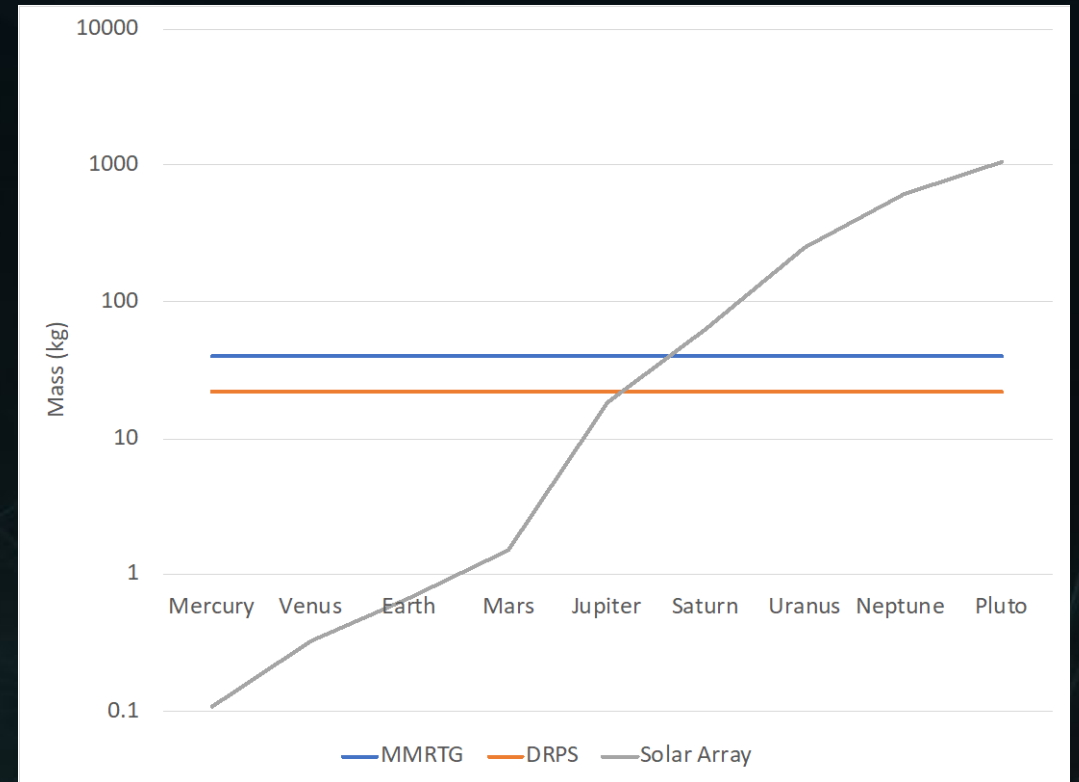
A Comparison of Radioisotope and Solar Array/Battery Power  
Systems in the Solar System

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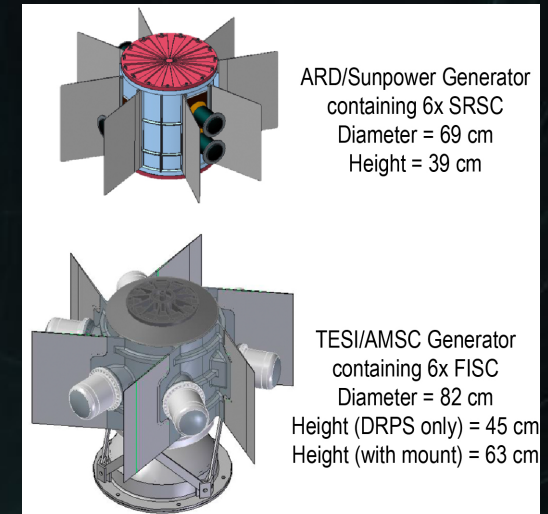
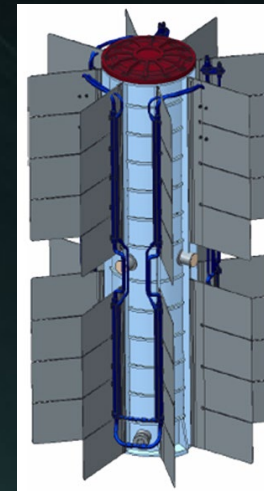
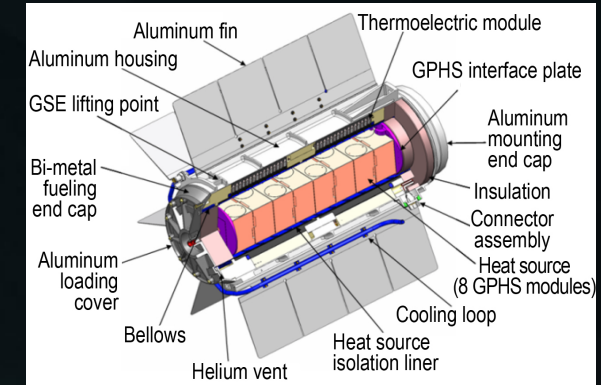
# Overview

- Request from Radioisotope Program Office for recreation of figure comparing RPS and solar power systems
- Figure shows the mass required to provide a continuous 100 watts at various orbital locations in the solar system
  - Tracking array
  - No periods of Darkness
  - No atmospheric attenuation
  - No energy storage
- Radioisotope Power Systems (RPS) are an enabling technology for missions where solar array/battery systems are impractical
  - Low solar intensity
  - Long duration of darkness
- Benefits of RPS
  - Relatively Constant power output
  - Waste heat for spacecraft



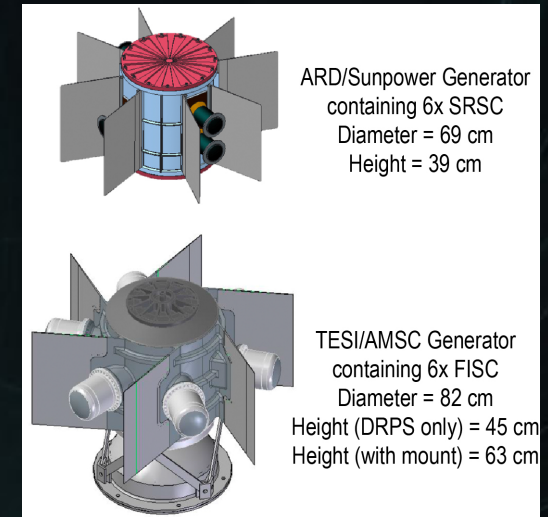
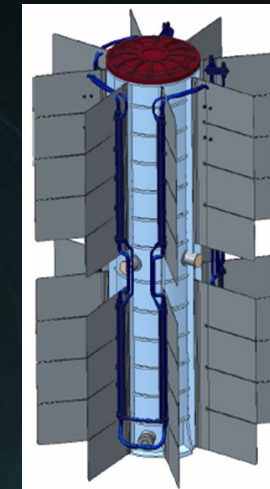
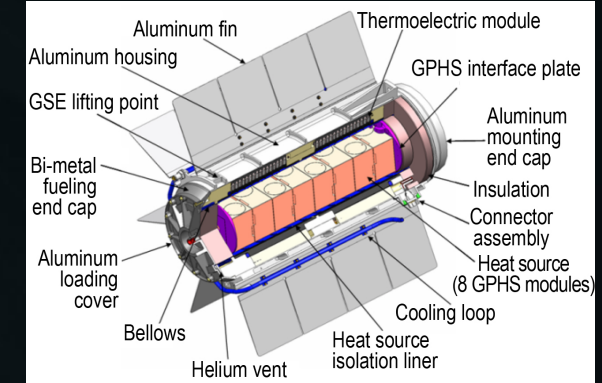
# Radioisotope Power Systems

- Multi-Mission Radioisotope Thermoelectric Generator is the only available generator from DOE
  - Capable of operating in gaseous or vacuum environments with atmosphere (i.e. Mars, Titan)
- NextGen RTG
  - Three Versions consideration
    - NextGen RTG Mod 0
      - Use of spare parts from GPHS RTG + possible accommodation of Step 2 GPHS modules
    - NextGen RTG Mod 1
      - GPHS RTG recreation to the extent possible with accommodation for larger GPHS (Step 0,1 to Step 2)
    - NextGen RTG Mod 2
      - New, higher performance thermoelectrics
  - Vacuum only operation
- Dynamic Radioisotope Power System (DRPS)
  - Stirling Convertors
  - High efficiency reduces isotope consumption
  - Requirements currently have multi mission capability



# Performance of RPS

	MMRTG	NextGen RTG Mod-1 Projected Performance	DRPS- Projected Performance
#GPHS	8 Step 2	16 Step 2	6 Step 2
Convertor	PbTe	SiGe	Stirling
BOL power output , watts	124	229	351
EODL power output, 17 yr, watts	70	165	283
BOL efficiency	6.2%	5.7%	23.4%
Degradation Rate (DR) (%/yr) Avg over 17 years (exp(-DR*time))	3.8 %/y	1.9 %/y	1.2 %/y
BOL specific power, W/kg	2.7	4.1	3.7
Waste Heat, watts	1876	3772	1149
Relative Micrometeoroid and Orbital Debris Susceptibility (MMOD)	High	Low	Medium



## Color Legend

Green – Available

Yellow – Small Deviation from GPHS RTG, high confidence in performance projections

Orange – New Power Convertors and Generator Design, some uncertainty in generator and convertor performance

# Lunar and Mars Operation

- MMRTG

- Lunar

- Not designed for lunar operation and may need modification when operating near equator
      - Lower initial heat inventory
      - Protection of TE modules from MMOD
      - White paint used to reduce solar input effectiveness may be reduced due to dust accumulation

- Mars

- Small reductions in power output due to atmosphere thermal environment (Curiosity MMRTG power output ranged from 109 to 119 during a Martian sol)
    - Generator appears to self clean via convection

- NextGen-Mod-0 through Mod-2

- Lunar

- Similar accommodations to MMRTG may be required at/near equator

- Mars

- Atmosphere precludes NextGen series from operation on Mars
    - Low pressure atmosphere would interact with both GPHS modules, thermoelectrics and other components

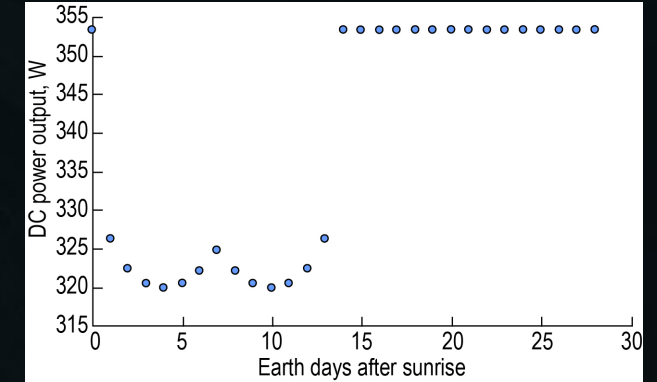
- DRPS

- Lunar

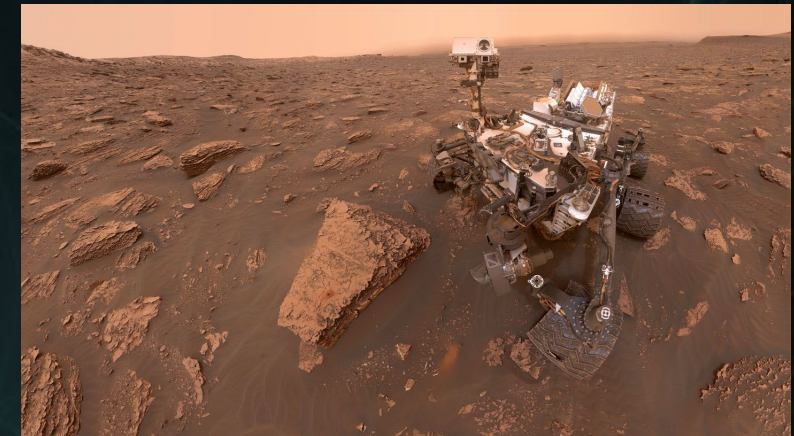
- Power Variations during lunar day/night cycle and location dependent
    - Current DRPS requirements should allow operation at the equator

- Mars

- Small power variation during Mars day/night and location dependent



Lunar Equatorial Power output of a 6 GPHS 8 Converter DRPS with dust covering heat rejection surfaces



# Other Solar System bodies

- Mercury

- Operation not possible during daylight for any of the RPS
- Operation in permanently shadowed regions or during 1408 hours of darkness should be possible and the performance should be close to that in deep space

- Venus

- 500 C surface temperatures and 95 Bars CO<sub>2</sub> precludes operation on surface for any of the RPS considered
  - Some preliminary design efforts to make a RPS system capable of surface operation have been explored but these designs are not extensible to other locations
- MMRTG or DRPS may be able to operate in the upper atmosphere but require mission accommodation

## Other Bodies Continued

- 7 moons have very thin atmosphere and MMRTG and DRPS should operate similar to deep space operation (Ganymede, Europa, Callisto, Rhea, Dione, Enceladus, and Titania )
- NextGen RTG will have difficulties on Triton and Io's with its thicker atmosphere (component atmospheric interaction, MLI thermal conductivity)
- NextGen RTG operation on Icy world surfaces is still unknown even with very low-pressure atmospheres
  - “It would generally seem that the physical process of water sublimation and diffusion into an RTG would be unfavorable, but the potential consequence of water as a strong oxidizing agent getting into a vacuum rated RTG is significant enough that further studies would be required to understand and properly mitigate this risk”

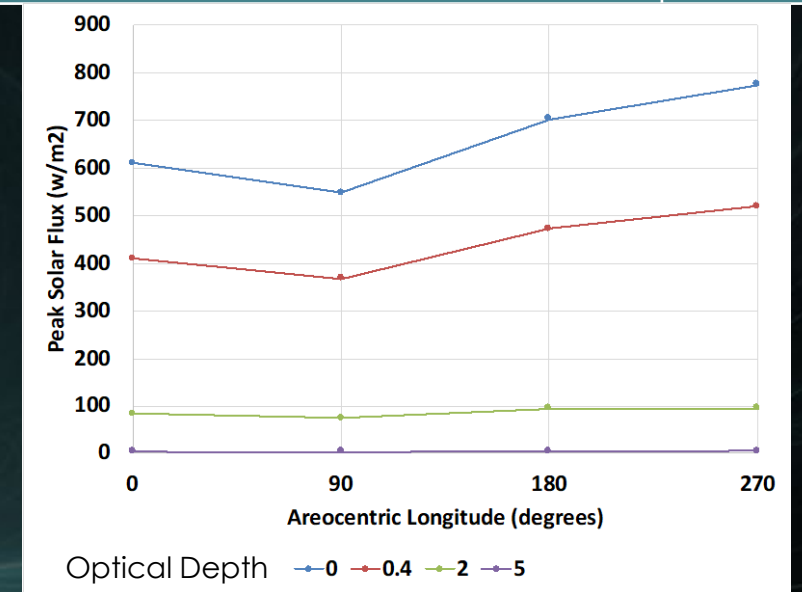
# SOA Solar Array and Battery

- Solar Intensity falls as  $1/\text{Distance}^2$
- Solar arrays are characterized by their areal power density ( $\text{w}/\text{m}^2$ ) and their Specific power ( $\text{w}/\text{kg}$ ) @1 AU and then adjusted for location
  - Values are based on Northrop Grumman's UltraFlex arrays on the Lucy Mission
- Mars operation was modeled for both Areocentric Longitude (i.e. time of year) and optical Depth
  - Optical depth values on Mars vary from about 0.4 for a clear day on Mars to 5.0 for a global dust storm.
    - Dust accumulation on arrays was not included
    - Largest recorded dust storm in 2018 had an optical depth >9 and caused Opportunity rover to stop working
- Titan
  - Atmospheric attenuation due to Titan's thick atmosphere is a 10-fold reduction in solar intensity
  - Surface Solar Intensity is  $\sim 1.5 \text{ w}/\text{m}^2$

TABLE 3. Battery Performance

Fold Out Flexible Array	
Conversion efficiency, %	32
Areal power density at 1 AU, $\text{W}/\text{m}^2$	415
Specific power at 1 AU, $\text{W}/\text{kg}$	184

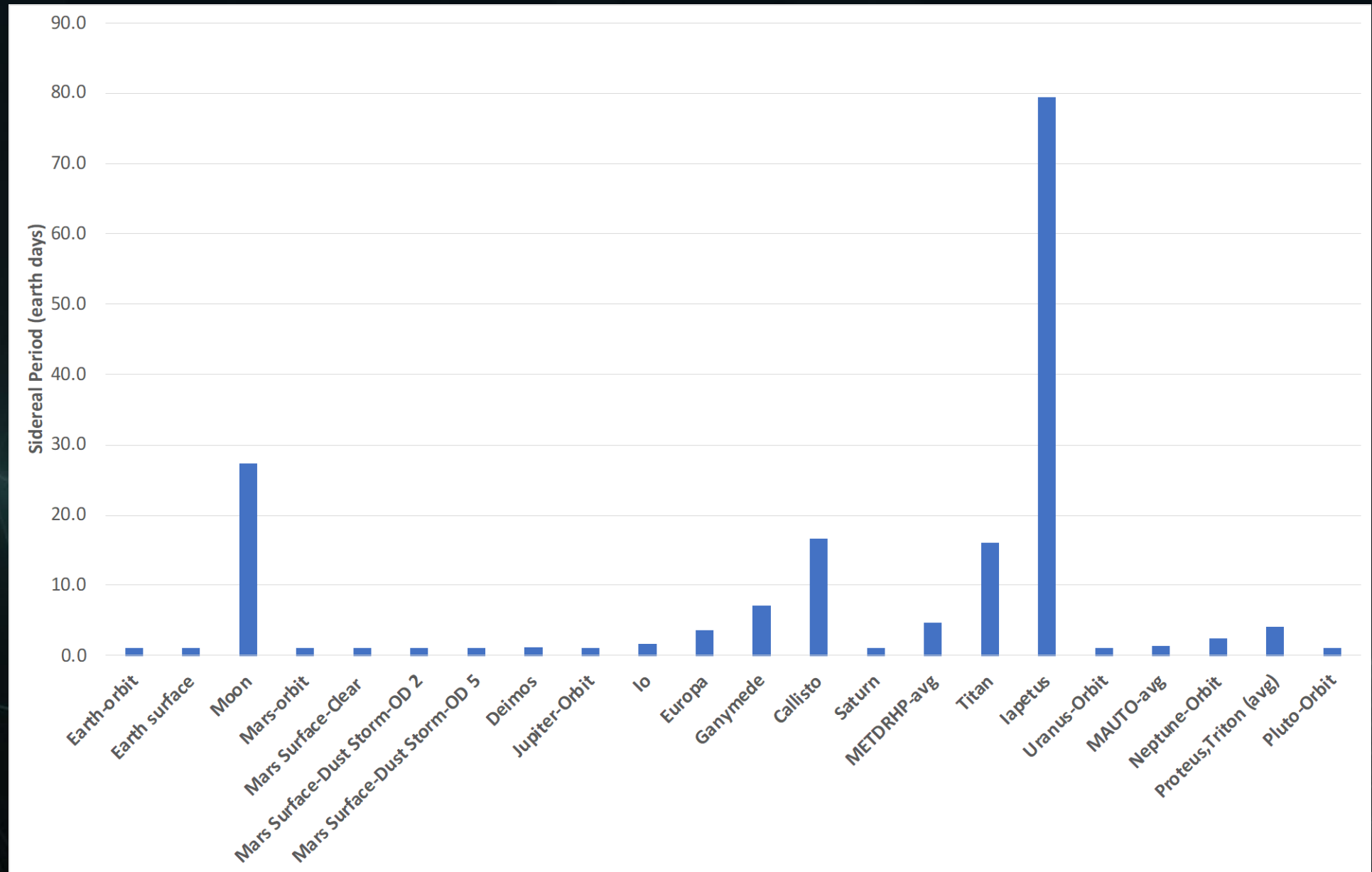
Lithium-Ion Battery SOA	
Specific energy, $\text{W}\cdot\text{h}/\text{kg}$	175
Gravimetric energy density, $\text{W}\cdot\text{h}/\text{liter}$	194
Depth-of-discharge, %	80
Charge/discharge efficiency, %	90



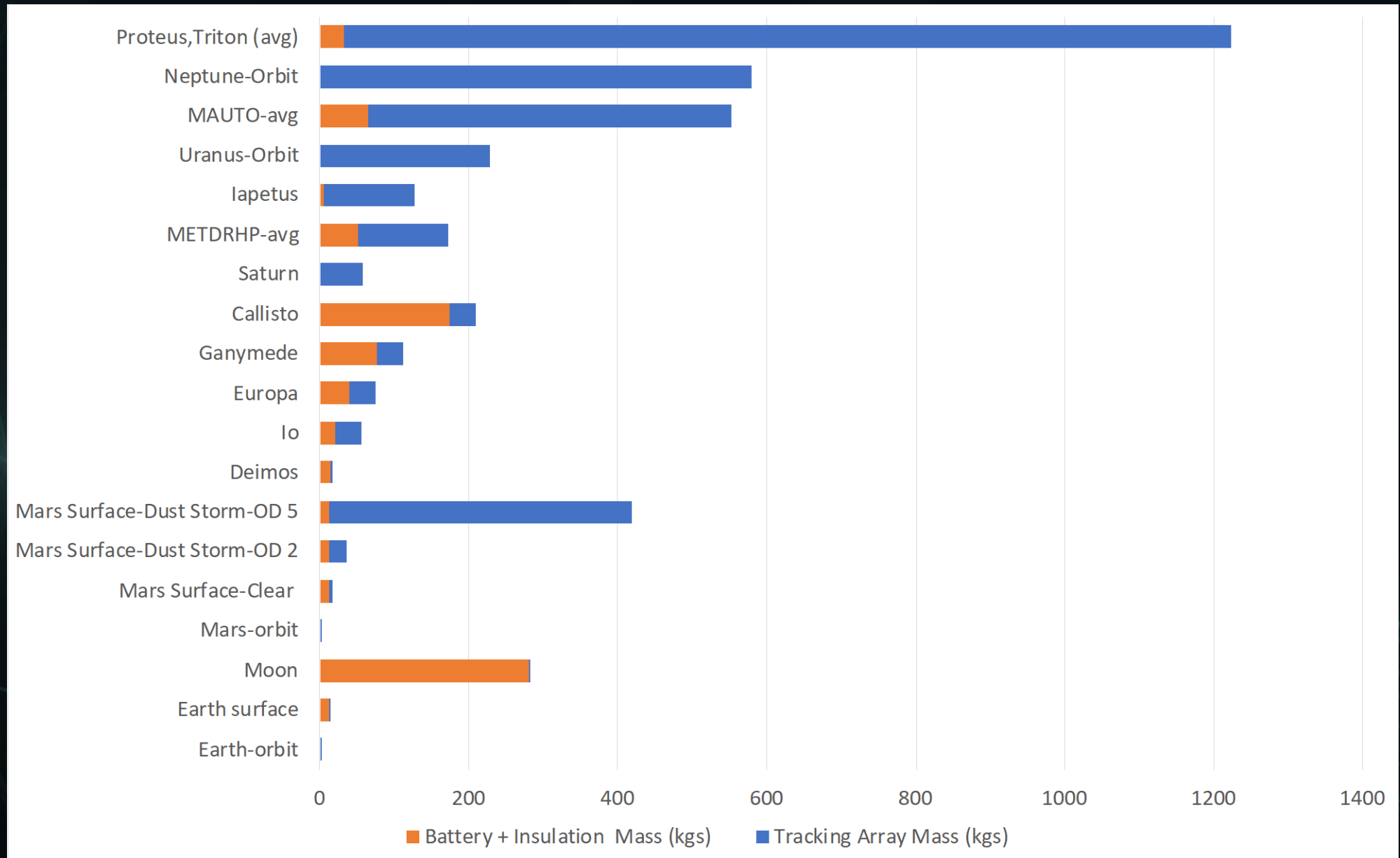
# Solar Array/Battery systems operation throughout solar system

- Most moons of the solar system are tidally locked, so the day equals the orbital solar period.
  - Uranus is unusual in that its axial tilt is so high that on its satellites the sun will rise and set only once per Uranus year unless the surface location is within about  $8^\circ$  of the equator.
  - Pluto similarly has such a high axial tilt to the plane of its orbit that any surface object more than  $33^\circ$  is in the polar regions.
- Following figures are for equatorial operation and show best case solar array and battery mass where day/night cycles are equal
  - Excluding polar regions which may have continuous illumination

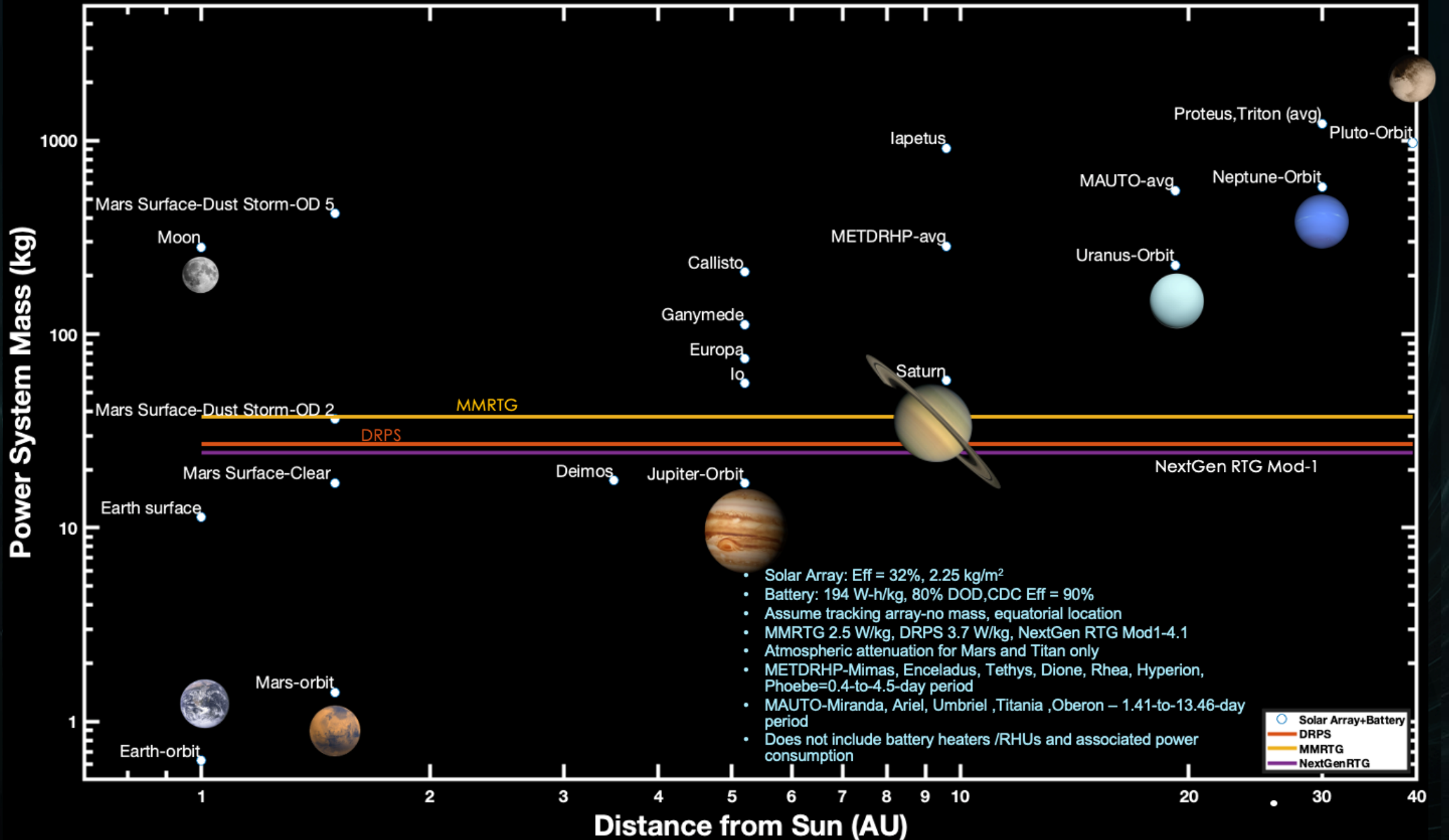
# Sidereal Period



# Array, Battery and Insulation Mass



# Providing 100 watts Continuous at Various Locations in the Solar System



# Conclusions

- Great progress has been made in both solar array and battery storage technologies, but nuclear systems are compelling and sometimes the only alternatives of power generation for many places in the solar system
- MMRTG and DRPS Multi-Mission capability is an important feature for future exploration of icy world and other bodies
- Each RPS has their own compelling characteristics

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