National Aeronautics and Space Administration

EXPLORE
SOLAR SYSTEM & BEYOND

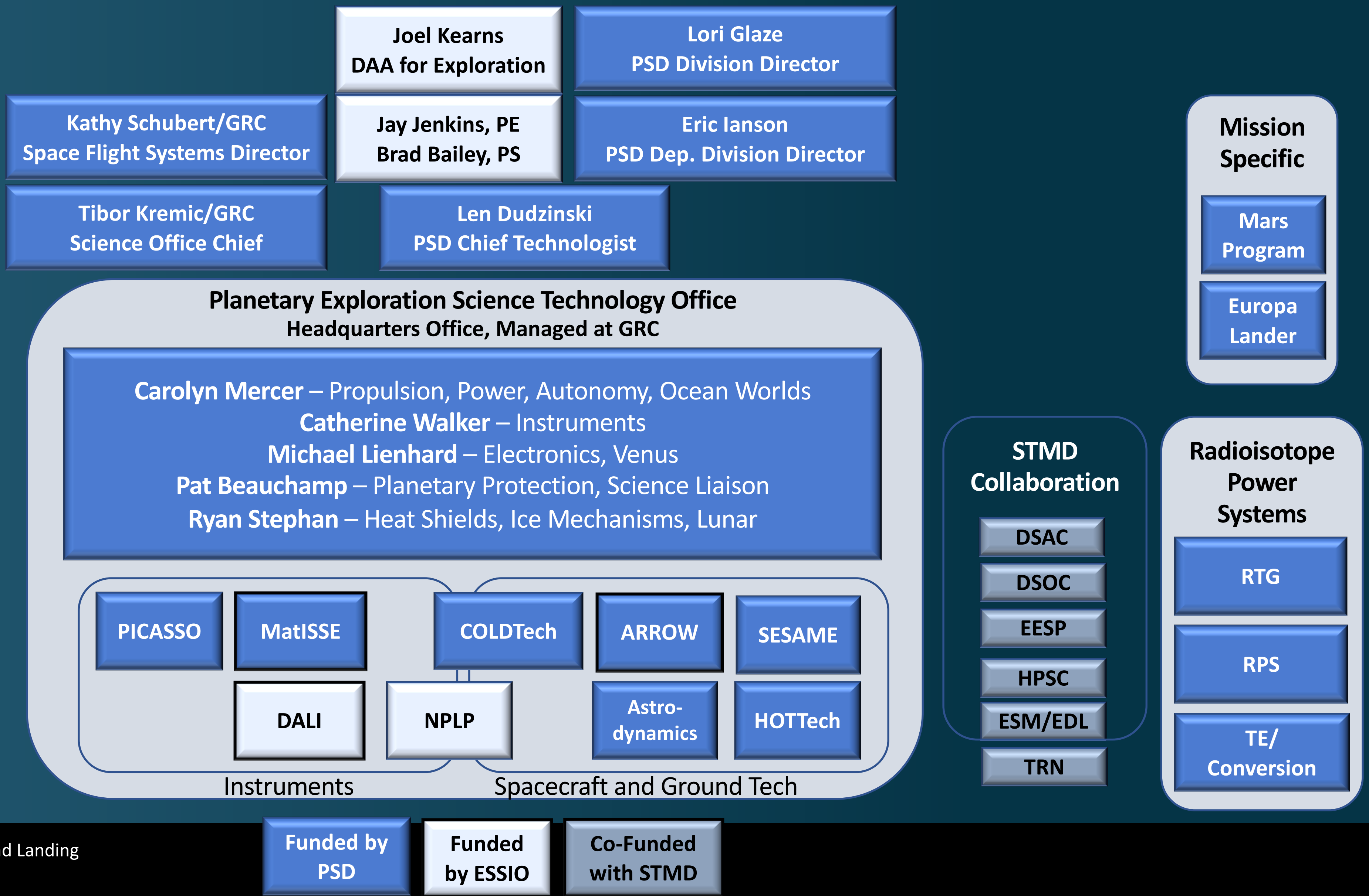
Planetary Science Technology Update

Carolyn Mercer
Manager, Planetary Exploration Science Technology Office (PESTO)

NASA Planetary Science Advisory Committee (PAC) Meeting
November 16, 2021

Planetary Science Division Technology Management

PESTO, Radioisotope Power Systems, Mission Specific, STMD Collaborations



RTG: Radioisotope Thermoelectric Generator
RPS: Radioisotope Power Systems
TE: Thermoelectric Conversion

DALI: Development and Advancement of Lunar Instrumentation
NPLP: NASA Provided Lunar Payloads
ARROW: Autonomous Robotics Research for Ocean Worlds
SESAME: Scientific Exploration Subsurface Access Mechanism for Europa

DSAC: Deep Space Atomic Clock
DSOC: Deep Space Optical Communications
EESP: Extreme Environment Solar Power
HPSC: High Performance Space Computing
ESM/EDL: Entry Systems Modeling/Entry Descent and Landing
TRN: Terrain Relative Navigation

Planetary Exploration Science Technology Office (PESTO) is chartered to:

- Recommend strategic technology investments to PSD
- Manage PSD technologies until they're adopted by missions
- Foster coordinated technology investments across NASA
- Promote technology infusion

Decadal Recommended Technologies: Visions and Voyages (no priority order)

- Science Instruments
- Survival In Extreme Environments
- In Situ Exploration
- Solar System Access and Other Core Technologies
- Technology Management

Technology Development for Planetary Science

Science Instruments, Spacecraft Technology

- **Planetary Exploration Science Technology Office (PESTO)**
  - Science Instruments (PICASSO, MatISSE, DALI, ICEE)
  - High Operating Temperature Technology (HOTTech)
  - Icy Satellites (COLDTech, SESAME, ARROW, Astrodynamics)
  - Core Technologies (PICA-D, ESM, GRAM, SKEP)

- **Mission Specific**
  - Europa Lander
  - Mars 2020, Mars Sample Return

- **Radioisotope Power Systems Program**
  - Next Gen Radioisotope Thermoelectric Generators (RTG)
  - Dynamic Radioisotope Power Systems (RPS)
  - Advanced Thermoelectrics and Conversion Technologies

- **Partnerships with STMD**
  - Entry, Descent, and Landing Systems
  - Technology Demonstrations (DSOC, EESP, DSAC)
  - SBIR
  - EPSCoR

Technology Development for Planetary Science
PESTO: Scientific Instruments

PICASSO

Any Science, Low TRL, Annual Solicitation

39 active tasks: Spectrometers, Imagers, LIDAR, X-ray Optics, UV Optics, GPR, Seismometers, Radiometers, Sample Capture, Tomography, …

MatISSE

Any Science, Mid TRL, Bi-annual Solicitation

24 active tasks: Accelerometer, Molecular Analyzers, Radiometers, Spectrometers, Radar, LIDAR, Geochronometer, Seismometers, …

DALI

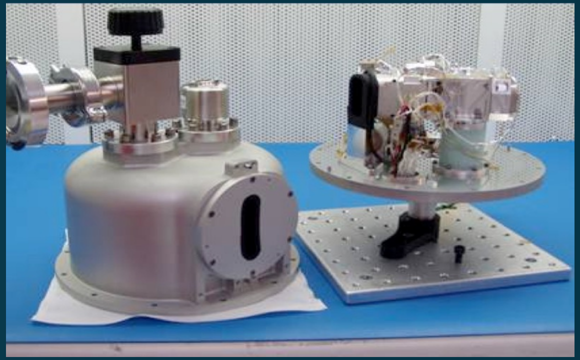
Lunar Science, Mid TRL, Annual Solicitation

20 active tasks: Imaging Spectrometer, Mass Spectrometer, Regolith Analyzers, Seismometers, Geochronometer, Dust Transport

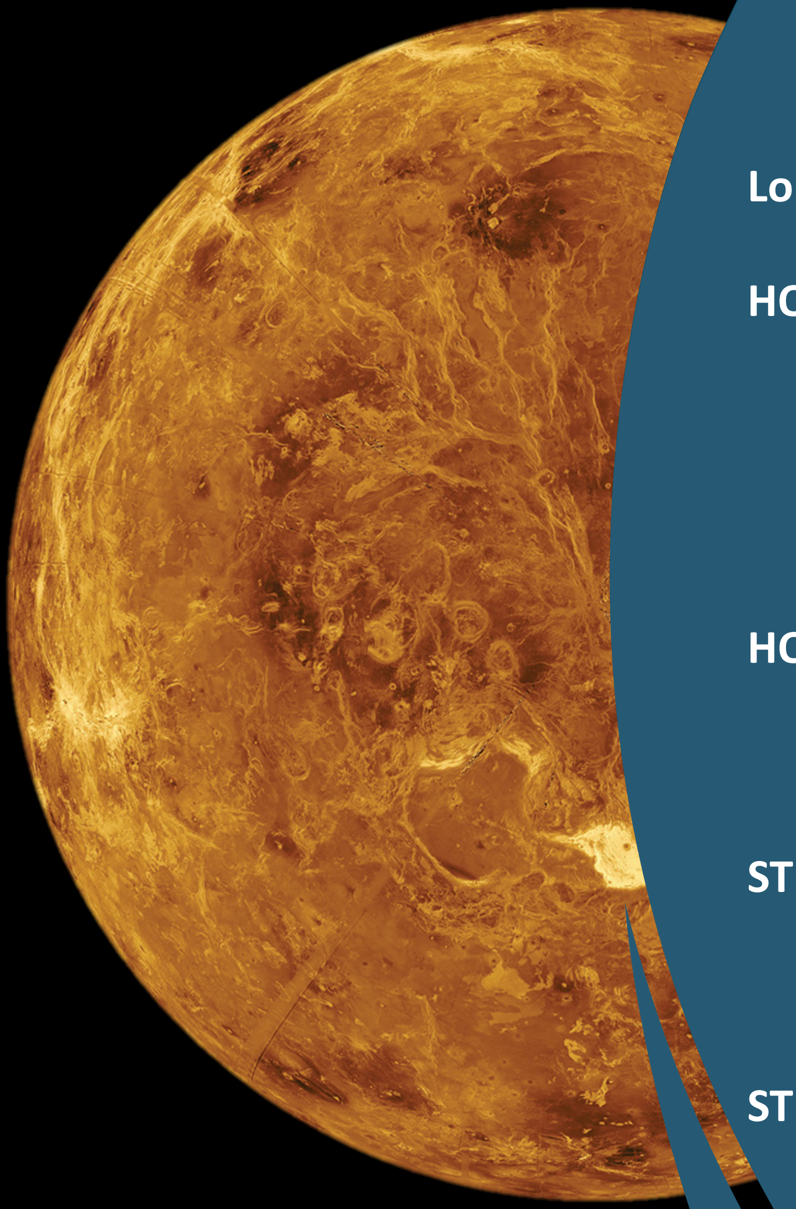
ICEE

Ocean World Science, Mid TRL, 2013 & 2018

14 tasks recently completed: Seismometers, Imagers, Mass Spectrometers, Raman Spectrometers, Organic Analyzers



MatISSE: Ultra Compact Imaging Spectrometer
PI: Diana Blaney



Technology Development for Planetary Science

PESTO: Venus Surface and Atmosphere

Long-Lived In Situ Solar System Explorer (LLISSE)

Batteries, Electronics, Sensors, Communications

HOTTech-2016

Electronics and Devices for Venus Surface Exploration 12 tasks:

Diamond and GaN Electronics, Memory, Clocks, Electronic Packaging, Motors, Batteries, Sensors, Solar Cells, Surface Power

HOTTech-2021

Electrical and Electronic Systems or Components for Venus Surface Exploration

STMD Small Business Innovative Research (SBIR)

Multiple Subtopics, including Venus focus for Aerial Platforms

STMD EPSCoR

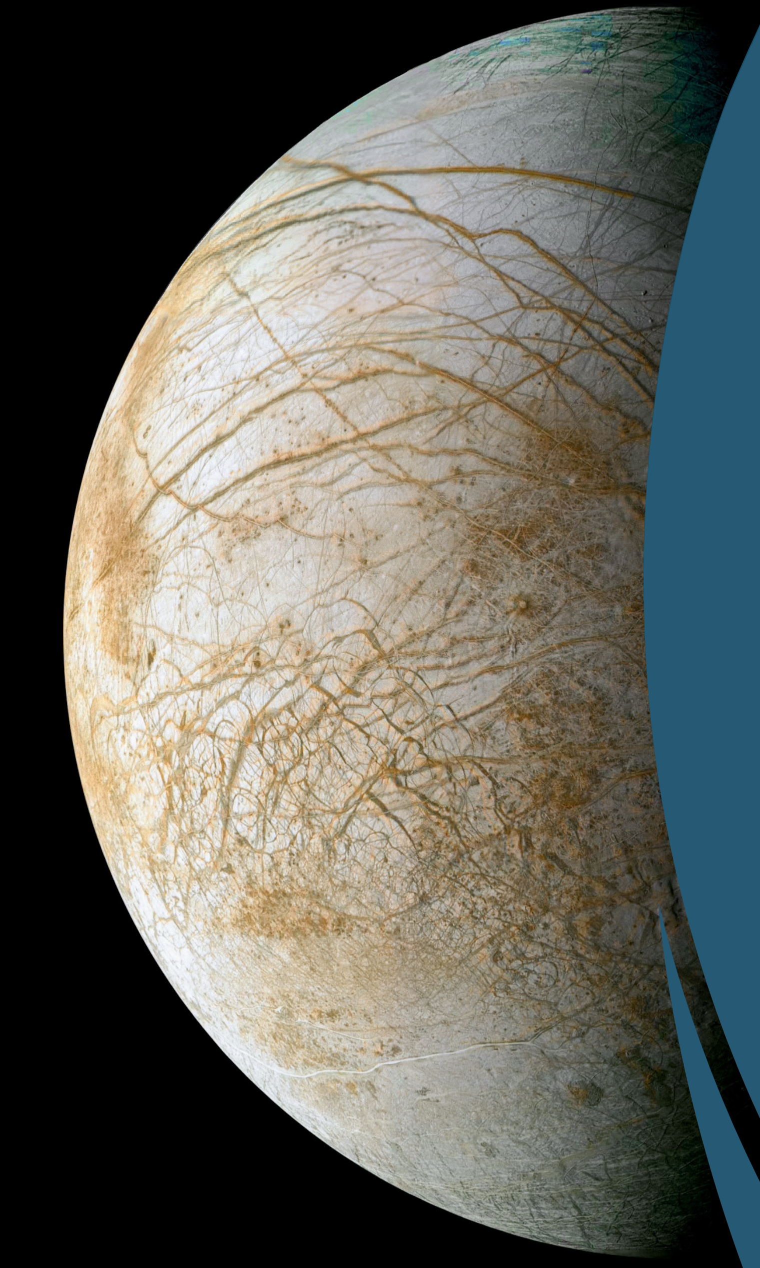
Venus Surface and Aerial Platform focus

HOTTech: High Temperature Chemical Sensor

PI: Darby Makel

Technology Development for Planetary Science

PESTO: Icy Satellites



COLDTech-2016

Instruments and Spacecraft Technologies for Surface and Subsurface Exploration. 21 tasks: Detection of evidence of life; Sample acquisition, delivery and analysis systems; Deep-ice access

SESAME

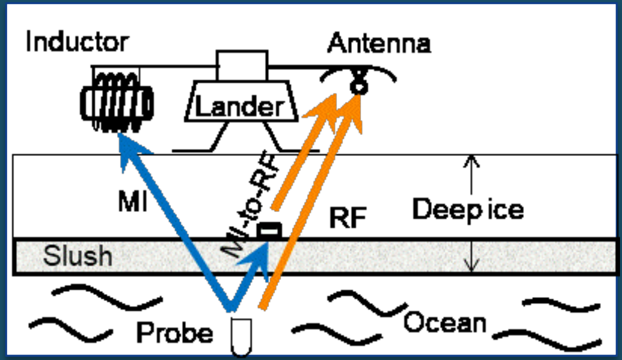
"Tall Pole" technologies for Vertical Ice Transport
5 tasks: Drills, Melt Probes, Communications

ARROW

Autonomy for Ocean World Surface Systems
2 tasks: Task Planning, Adaptive Software

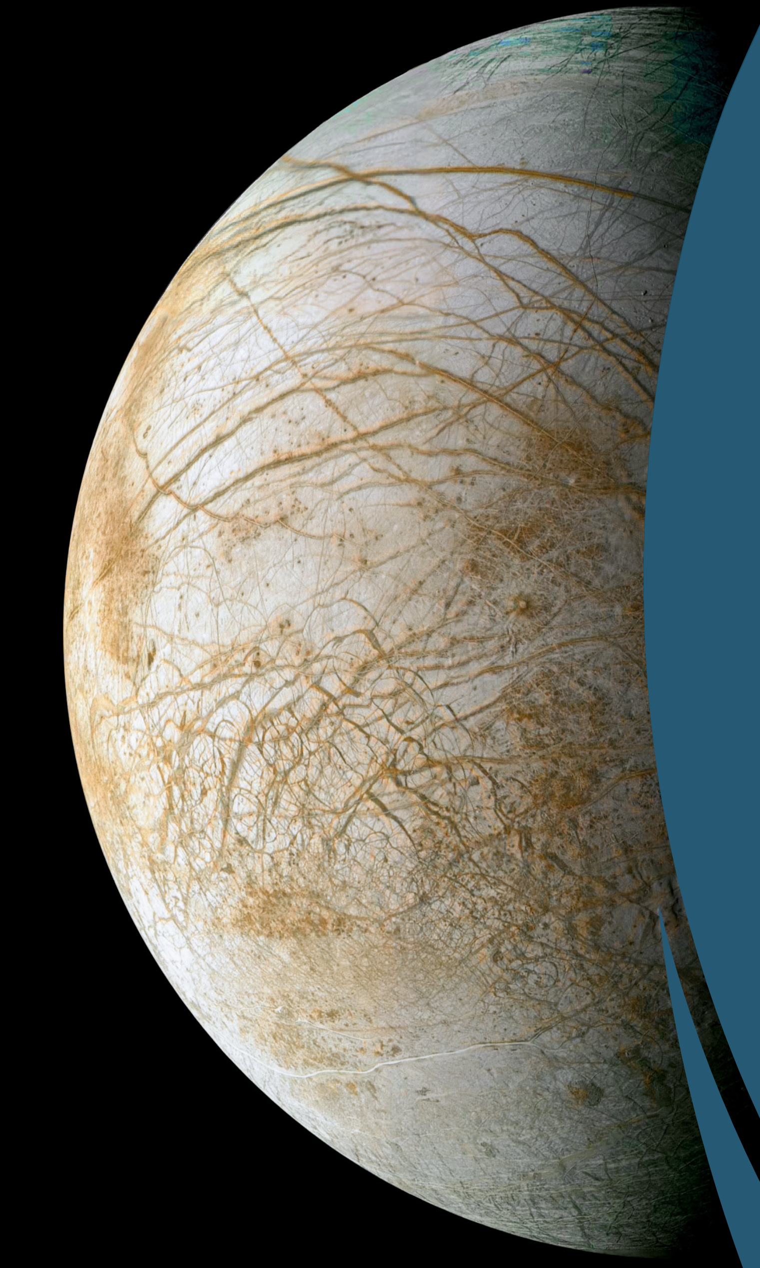
COLDTech-2020 (SESAME and ARROW follow-on plus)

11 tasks: Through-the-Ice Communications, Radiation Hard Electronics, Autonomy



COLDTech: Hybrid RF/MI Transceiver for Europa Sub-Ice Communications
PI: Michael Chang

Mission Specific: Europa Lander



Autonomy

- Sampling Autonomy: Develop and validate functional level autonomy for test excavation, sampling, and sample transfer
- Surface Mission Autonomy: In-depth exploration of architectural and system issues that enable and constrain onboard autonomy (hardware, software, sensors, etc.)

Communications

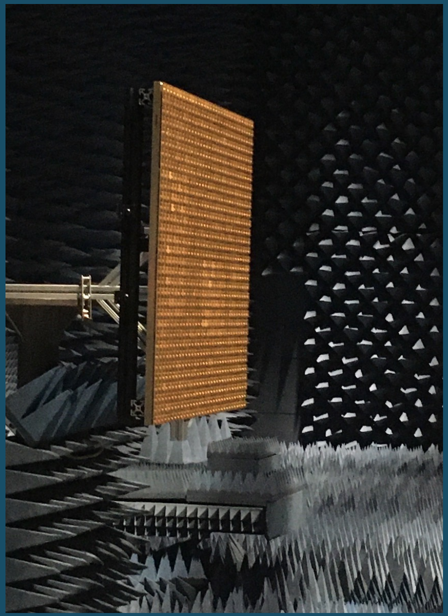
- High Gain Antenna: Mature the Europa Lander High Gain Antenna design to TRL-6

Power

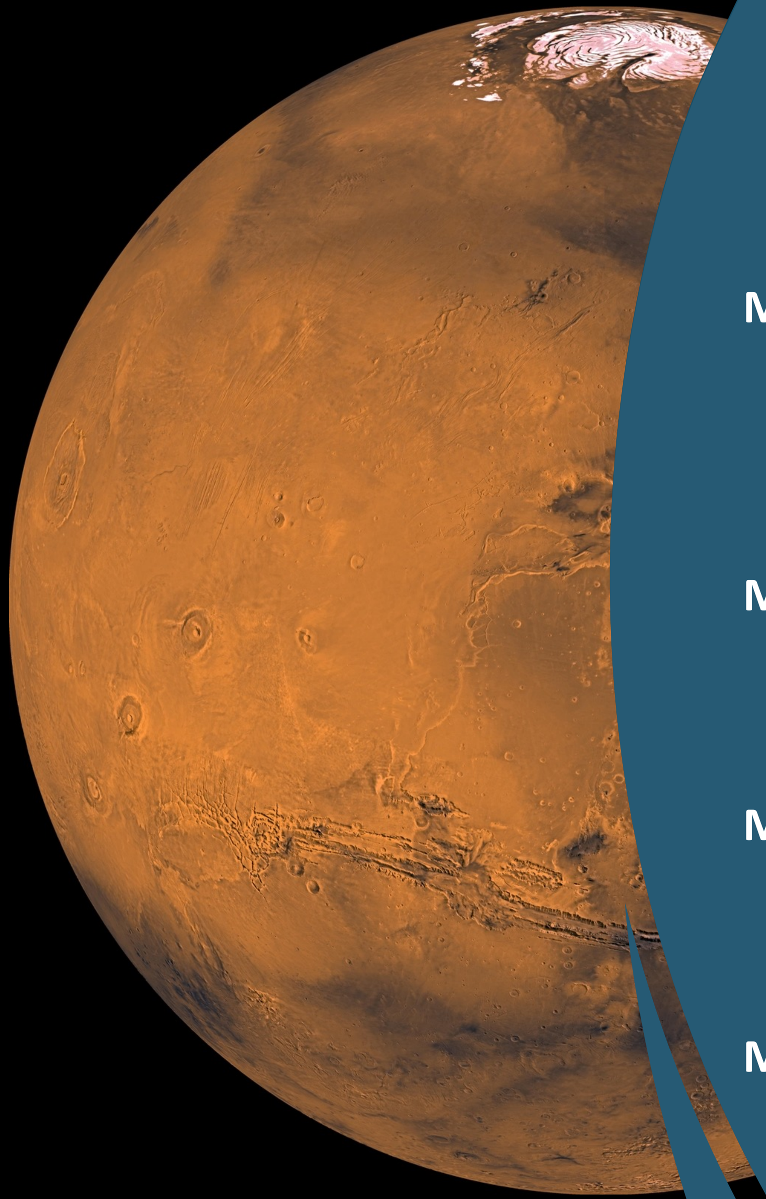
- Battery: Evaluate effects of long-term storage and radiation on key cell characteristics (performance, safety, Li/CF_x primary cells)

De-orbit, Descent, Landing (DDL)

- LIDAR Systems: Investigate LIDAR-based map-relative localization for Europa DDL



Europa Lander: High Gain Antenna (NASA JPL)



Technology Development for Planetary Science

Mission Specific: Mars

Mars 2020: Ingenuity Helicopter

Co-funded with STMD and Aeronautics

Guidance, navigation and control; IMM solar cell demonstration

Mars 2020: Terrain Relative Navigation

Co-funded with STMD

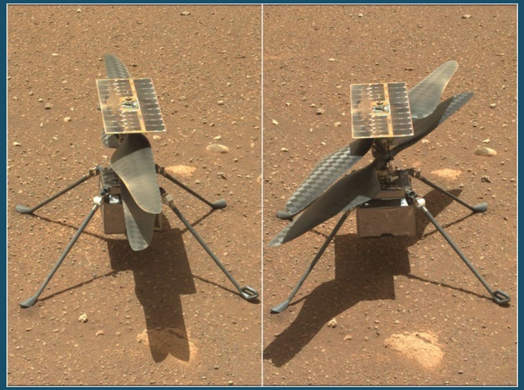
Vision system, Target selection algorithms

Mars 2020: Autonomy

Rover driving, Robotic arm operations, Science instrument operations

Mars Sample Return:

Sample handling, Propulsion, Spring-loaded tires, Heatshield, Brazing technique, Parachute, Impact structure



Ingenuity
(NASA JPL)

Technology Development for Planetary Science
PESTO: Other Core Technologies

PICA-D
Upgraded commercial manufacturing line and switched from foreign-sourced Rayon to domestic-sourced Lyocell.

Entry Systems Modeling (ESM)
Predictive materials modeling, Shock layer kinetics and radiation,
Guidance navigation and control,
Computational and experimental aerosciences

Global Reference Atmospheric Model (GRAM)
Engineering-oriented atmospheric model that estimates mean values and statistical variations of atmospheric properties for planetary destinations

SmallSat Electric Propulsion
Hall effect thruster (<1kW) development in conjunction with STMD's Announcement of Collaborative Opportunity award

Extreme Environment Solar Power (EESP) – tech demo on DART
Deep Space Optical Communications (DSOC) – tech demo on Psyche
Deep Space Atomic Clock (DSAC) – tech demo on Veritas

Technology Development for Planetary Science
Radioisotope Power Systems

Next Gen Radioisotope Thermoelectric Generators (RTG)

Next Gen System with a performance no less than the GPHS-RTG system in order to support a 2030 mission: Deliver Mod 0 (refurbished GPHS-RTG); Mod 1 (new capability to produce GPHS-RTGs)

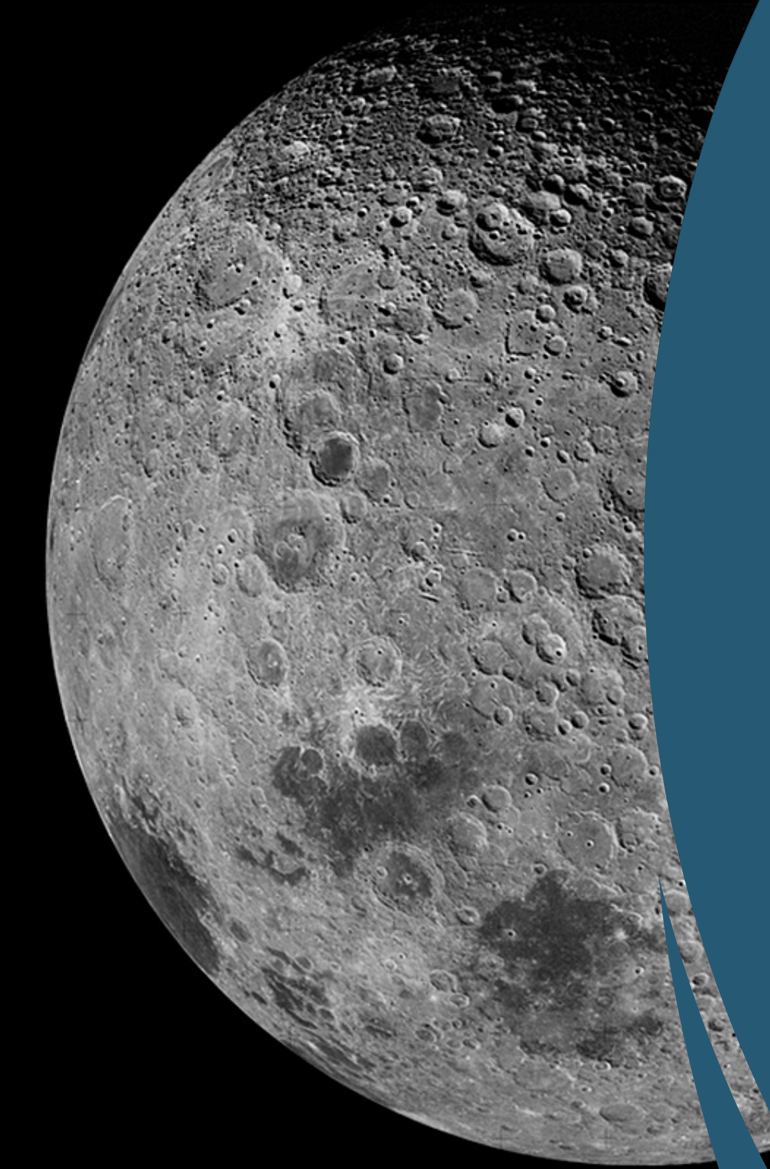
Increase the conversion efficiency as compared to the GPHS-RTG with a goal of 290 We EODL: Lanthanum/Tellurium/Zintl thermoelectric couples

Dynamic Radioisotope Power Systems (DRPS)

Multi-Mission RPS with an efficiency of 20-25% and produce 300-400 W_e of electrical power: Gas Bearing Stirling Convertor; Flexture Stirling Convertor; Controller Maturation; Risk Informed Life Testing, Generator System

Advanced Thermoelectrics and Conversion technologies

Increase system efficiency and decrease system degradation rate: SKD Thermoelectrics; Small Stirling Technology Exploration Power (SmallSTEP); Group for the HOlistic Science of Thermoelectrics (GHOST); Johnson Thermo-Electrochemical Convertor (JTEC)



Technology Development for Planetary Science

Space Technology Mission Directorate: The Moon and More

Technology Maturation

Lunar Surface Innovation Initiative

Power systems, Dust mitigation systems, Surface excavation systems, Extreme access mobility systems, Mechanisms and Electronics

Game Changing Technology Development Program

Entry Systems Modeling, High Performance Spaceflight Computing, Mars Entry/Descent/Landing Instrumentation, Cooperative Autonomous Distributed Robotic Exploration, Bulk Metallic Glass Gears, Extreme Environment Solar Power

Technology Demonstrations

Deep Space Optical Communications, Laser Communications Relay, Solar Electric Propulsion, Terrain Relative Navigation, Green Propellant, Fission Surface Power, Deep Space Atomic Clock, Small Spacecraft Technology

SBIR/STTR, EPSCoR, NIAC, STRG, ECI

Technology in yellow has flown or will fly on PSD missions

Questions?

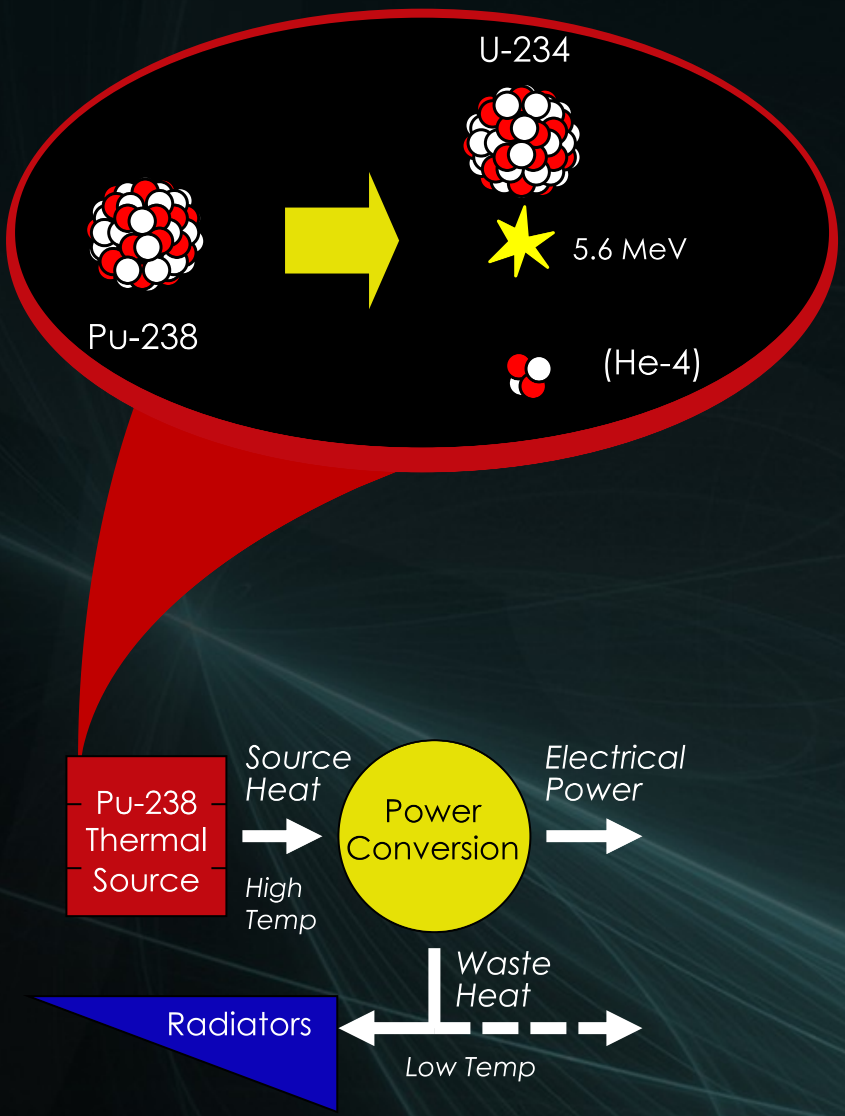
National Aeronautics and
Space Administration

RADIOISOTOPE POWER SYSTEMS PROGRAM

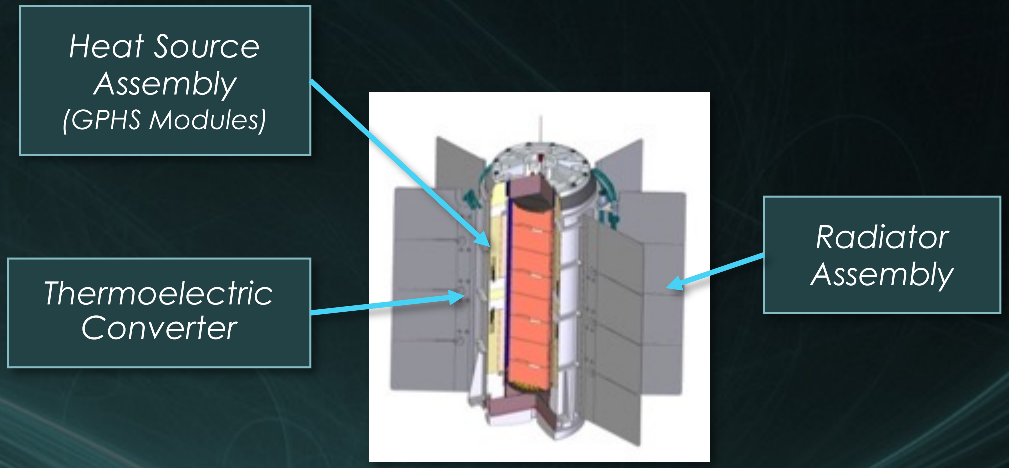
Presentation to
Planetary Advisory Committee
November 16, 2021

Leonard A. Dudzinski
Planetary Science Chief Technologist
NASA Headquarters

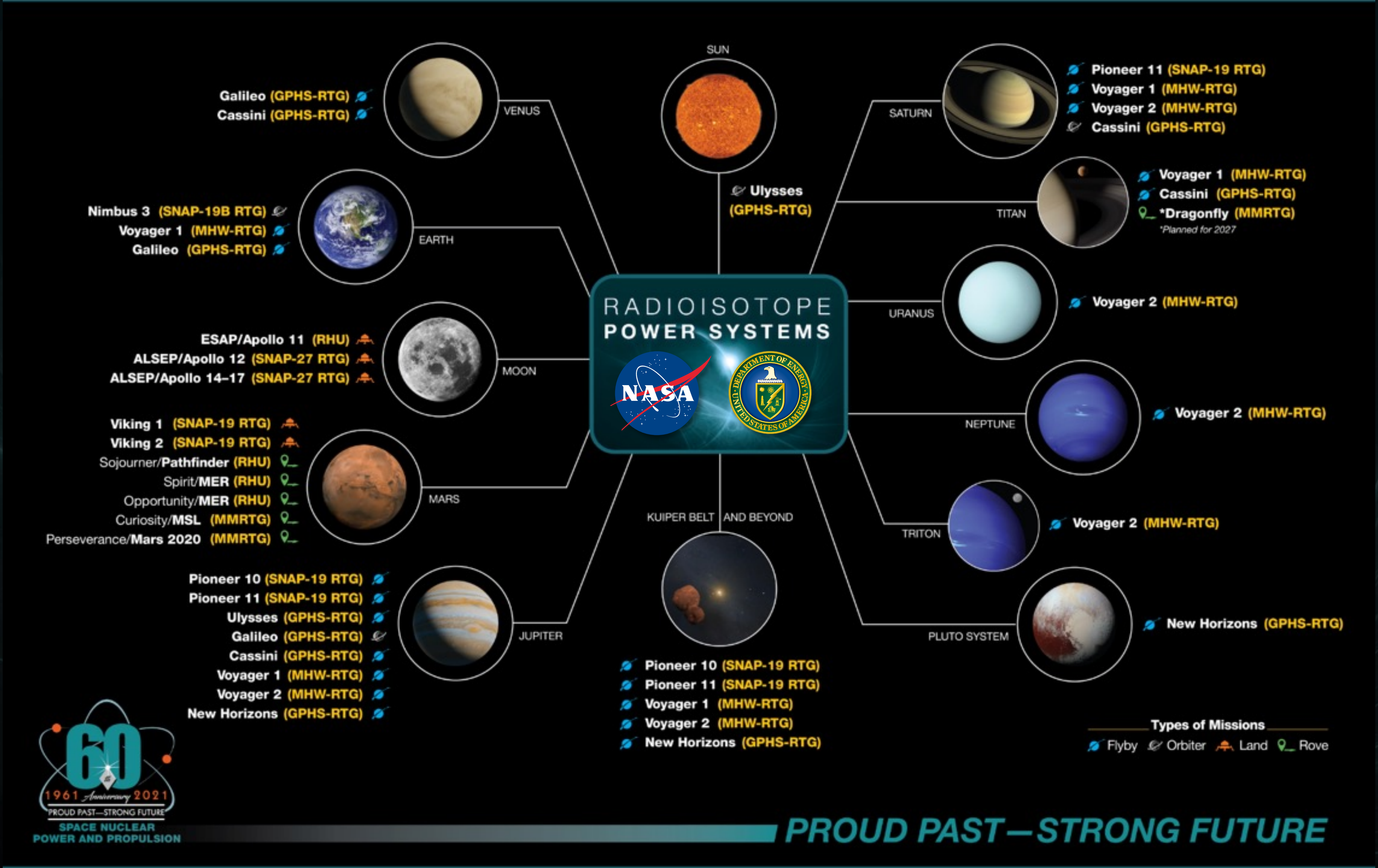
Radioisotope Power Systems (RPS)



- Heat produced from natural alpha particle decay of Plutonium (Pu-238)
  - 87.7-year half-life
- Small portion of heat energy (6%-35%) converted to electricity via passive or dynamic processes
  - Thermoelectric (existing & under development)
  - Stirling, Brayton (under development)
  - Thermophotovoltaic, Thermionic, Ericsson, etc. (future candidates)
- Waste heat rejected through radiators – portion can be used for thermal control of spacecraft subsystems



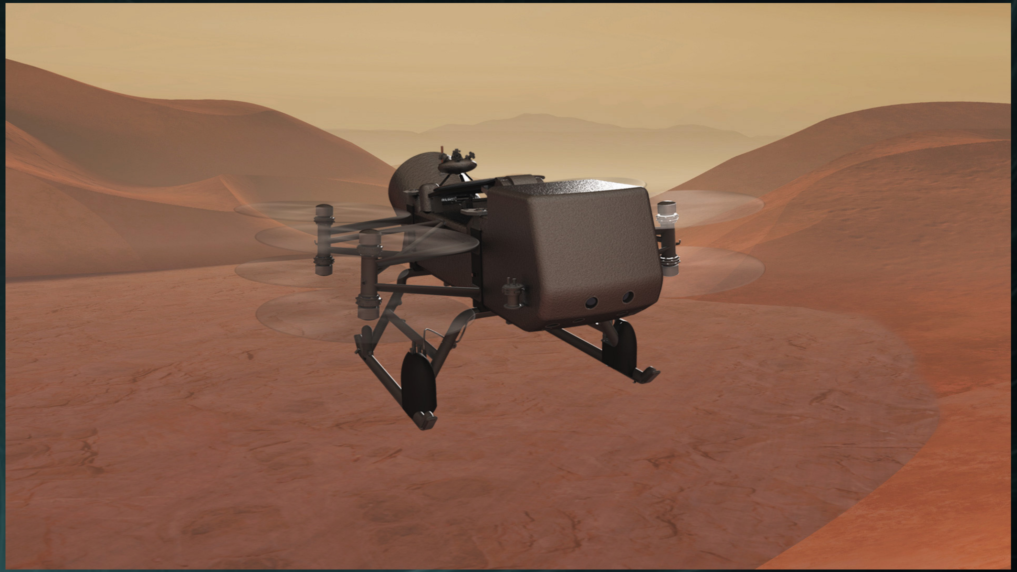
Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)


RADIOISOTOPE
POWER SYSTEMS
NASA
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA
SUN
Ulysses (GPHS-RTG)
VENUS
Galileo (GPHS-RTG)
Cassini (GPHS-RTG)
EARTH
Nimbus 3 (SNAP-19B RTG)
Voyager 1 (MHW-RTG)
Galileo (GPHS-RTG)
MOON
ESAP/Apollo 11 (RHU)
ALSEP/Apollo 12 (SNAP-27 RTG)
ALSEP/Apollo 14–17 (SNAP-27 RTG)
MARS
Viking 1 (SNAP-19 RTG)
Viking 2 (SNAP-19 RTG)
Sojourner/Pathfinder (RHU)
Spirit/MER (RHU)
Opportunity/MER (RHU)
Curiosity/MSL (MMRTG)
Perseverance/Mars 2020 (MMRTG)
JUPITER
Pioneer 10 (SNAP-19 RTG)
Pioneer 11 (SNAP-19 RTG)
Ulysses (GPHS-RTG)
Galileo (GPHS-RTG)
Cassini (GPHS-RTG)
Voyager 1 (MHW-RTG)
Voyager 2 (MHW-RTG)
New Horizons (GPHS-RTG)
KUIPER BELT AND BEYOND
Pioneer 10 (SNAP-19 RTG)
Pioneer 11 (SNAP-19 RTG)
Voyager 1 (MHW-RTG)
Voyager 2 (MHW-RTG)
New Horizons (GPHS-RTG)
SATURN
Pioneer 11 (SNAP-19 RTG)
Voyager 1 (MHW-RTG)
Voyager 2 (MHW-RTG)
Cassini (GPHS-RTG)
TITAN
Voyager 1 (MHW-RTG)
Cassini (GPHS-RTG)
*Dragonfly (MMRTG)
*Planned for 2027
URANUS
Voyager 2 (MHW-RTG)
NEPTUNE
Voyager 2 (MHW-RTG)
TRITON
Voyager 2 (MHW-RTG)
PLUTO SYSTEM
New Horizons (GPHS-RTG)
Types of Missions
Flyby
Orbiter
Land
Rove
60
1961 Anniversary 2021
PROUD PAST—STRONG FUTURE
SPACE NUCLEAR
POWER AND PROPULSION
PROUD PAST—STRONG FUTURE

NASA Current RPS Missions: **The Power to Explore**

- Perseverance
  - Launched in July 2020
  - Seeking signs of ancient life and collecting rock and soil sample
  - Provided an MMRTG under budget, ahead of schedule, above power, during the COVID-19 pandemic

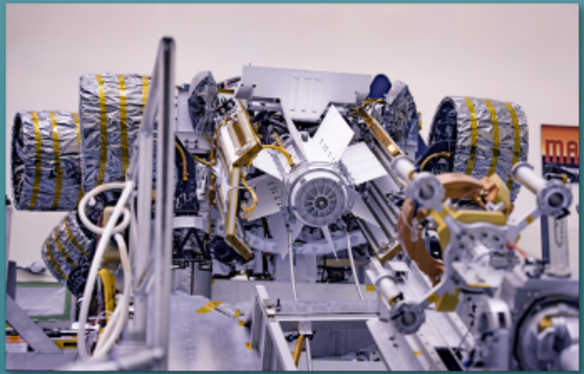
- Dragonfly
  - Flights to explore Saturn's moon Titan, an organic-rich ocean world
  - Planned launch in 2026
  - A Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) will enable Dragonfly to explore beneath the thick, hazy atmosphere of Titan



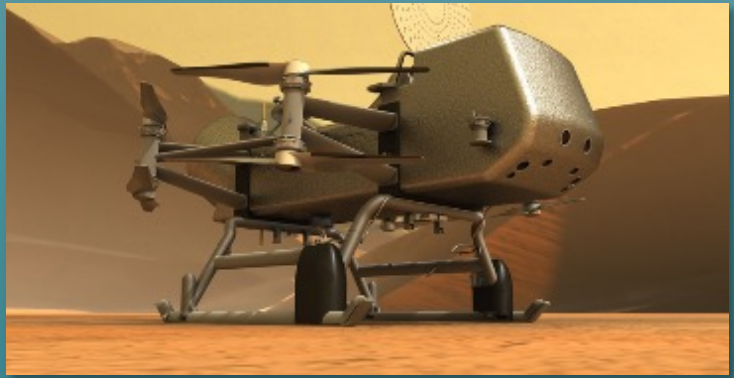
RPS Program's Core Purpose

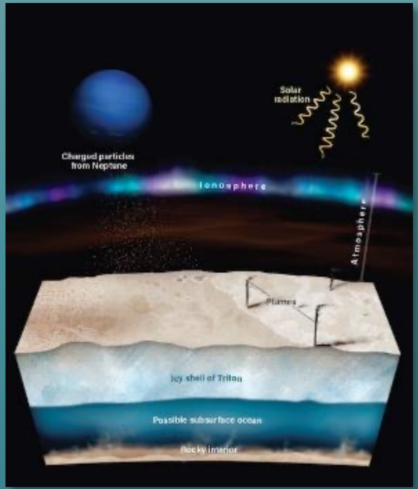
- Deliver reliable radioisotope power systems to enable science and exploration missions resulting in the following tangible outcomes over time

✓ Flights of RPS powered strategic/directed missions



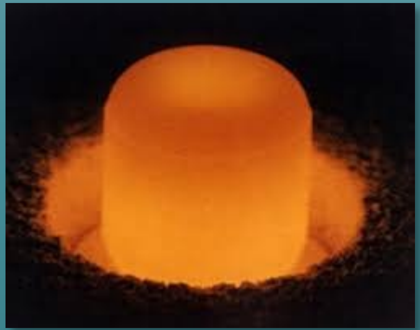
✓ Flights of RPS powered Discovery class and/or New Frontiers class missions



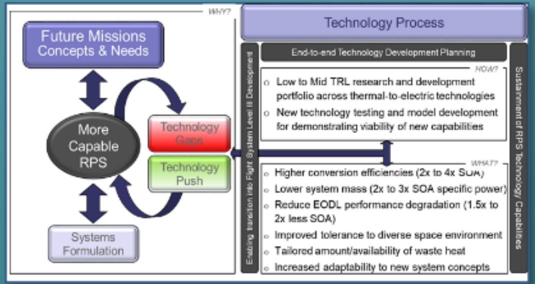


✓ Efficient and cost effective NEPA and launch authorization

✓ Achievement of constant rate production (CRP) U.S. Pu-238 isotope production capability aligned to NASA mission needs

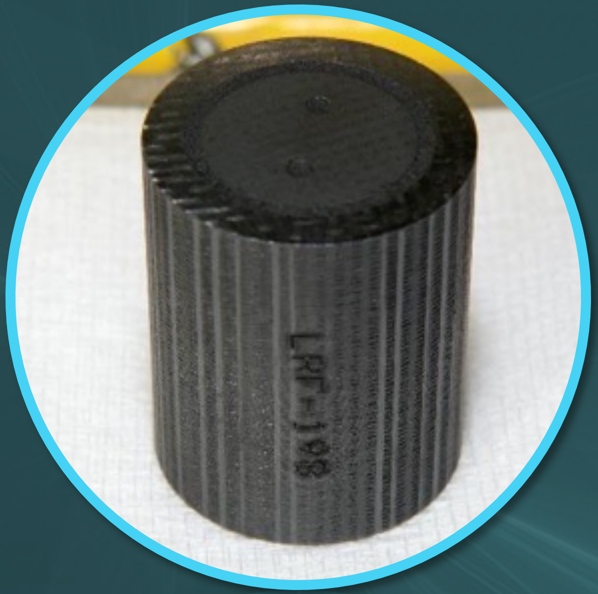


➢ Increased energy conversion efficiency as compared to 2009 RPS capabilities



Technology Investments
Enable New Radioisotope Generators

Radioisotope Power System Heat Source



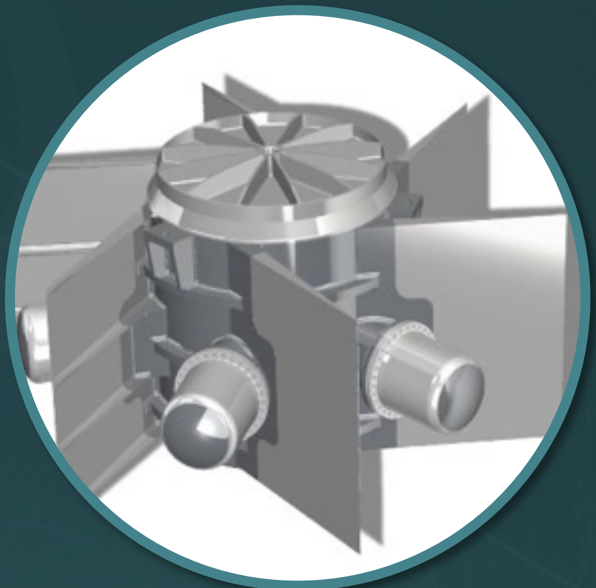
LWRHU

Light Weight Radioisotope Heater Units

Multi-Mission Radioisotope Power System

MMRTG

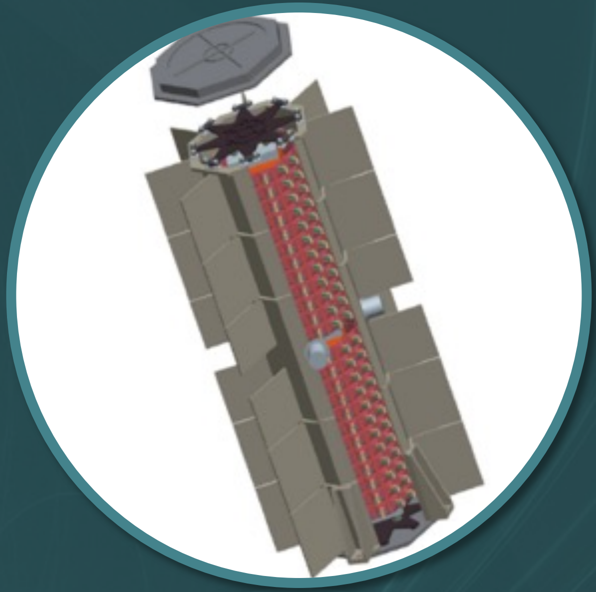
Multi-Mission Radioisotope Thermoelectric Generator



DRPS

Dynamic Radioisotope Power System

Vacuum Rated Radioisotope Power System



Next Gen RTG

Next Generation Radioisotope Thermoelectric Generator

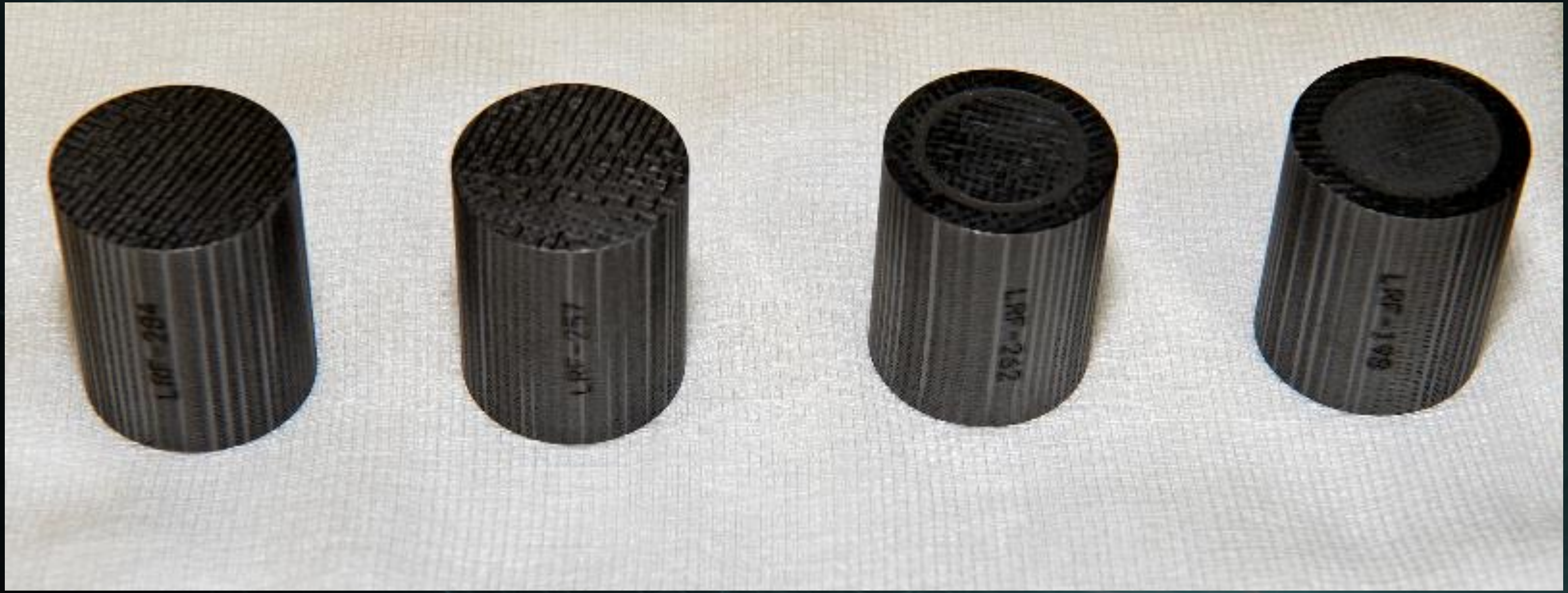
Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

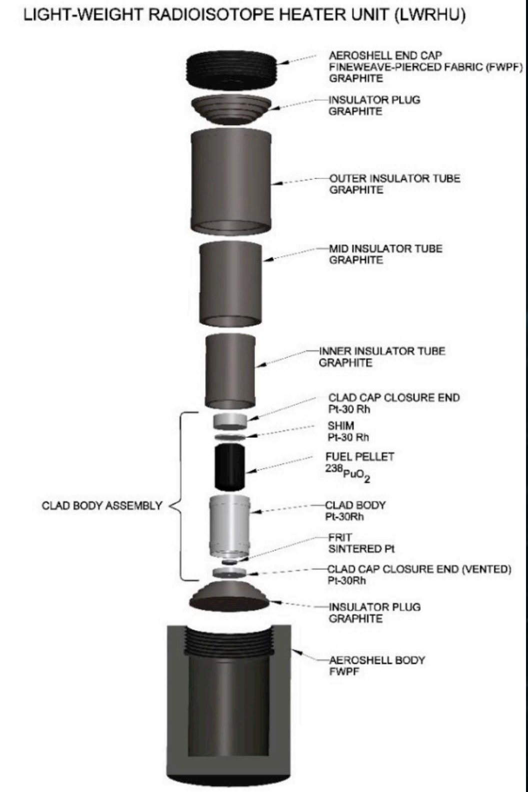
- **F1** on Mars on Curiosity
  - Current Power 82.9 W_e
- **F2** on Mars on Perseverance
  - Current Power 112.7 W_e
- **F3** at INL ready for a mission
  - Completed 1–MMRTG 48-couple module
- **F4** under contract

* Current as of August 2021

Lightweight Radioisotope Heater Units (LWRHU)

- LWRHU provide heat for missions
  - Current LWRHU inventory available
  - DOE developed plan for reconstituted LWRHUs
    - Complete ORNL hardware capability in place
    - Portions of LANL capability in place
- LWRHU Programmatic EA completed
- LWRHU System-Specific DSA to be completed 2021





Next Gen Mod 1 = ~GPHS-RTG

- A revectored design of the **heritage GPHS-RTG** was the results of a DOE Phase 1 industry effort for a new technology-based system
- Aerojet Rocketdyne under INL letter contract
- Reestablish GPHS RTG production capability by 2027
  - Use of proven heritage design with proven long life and low degradation
  - More cost effective
  - Less risk
- 90% heritage design, but lower heat; lower power; 2 trades going on to consider change to stretch the housing; more efficiency of the couples; EODL~177-210 W_e
- Maintains opportunity for enhancements providing increased performance & greater efficiency (Mod 2)






LES 8*
Mar. 14, 1976–2004
2 MHW RTG: 158 W_e BOL

LES 9*
Mar. 14, 1976–2020
2 MHW RTG: 158 W_e BOL

Cassini
Oct. 15, 1997–2017
3 GPHS RTG: @~292 W_e BOL

New Horizons
Jan. 19, 2006–Present
GPHS RTG: 245 W_e BOL

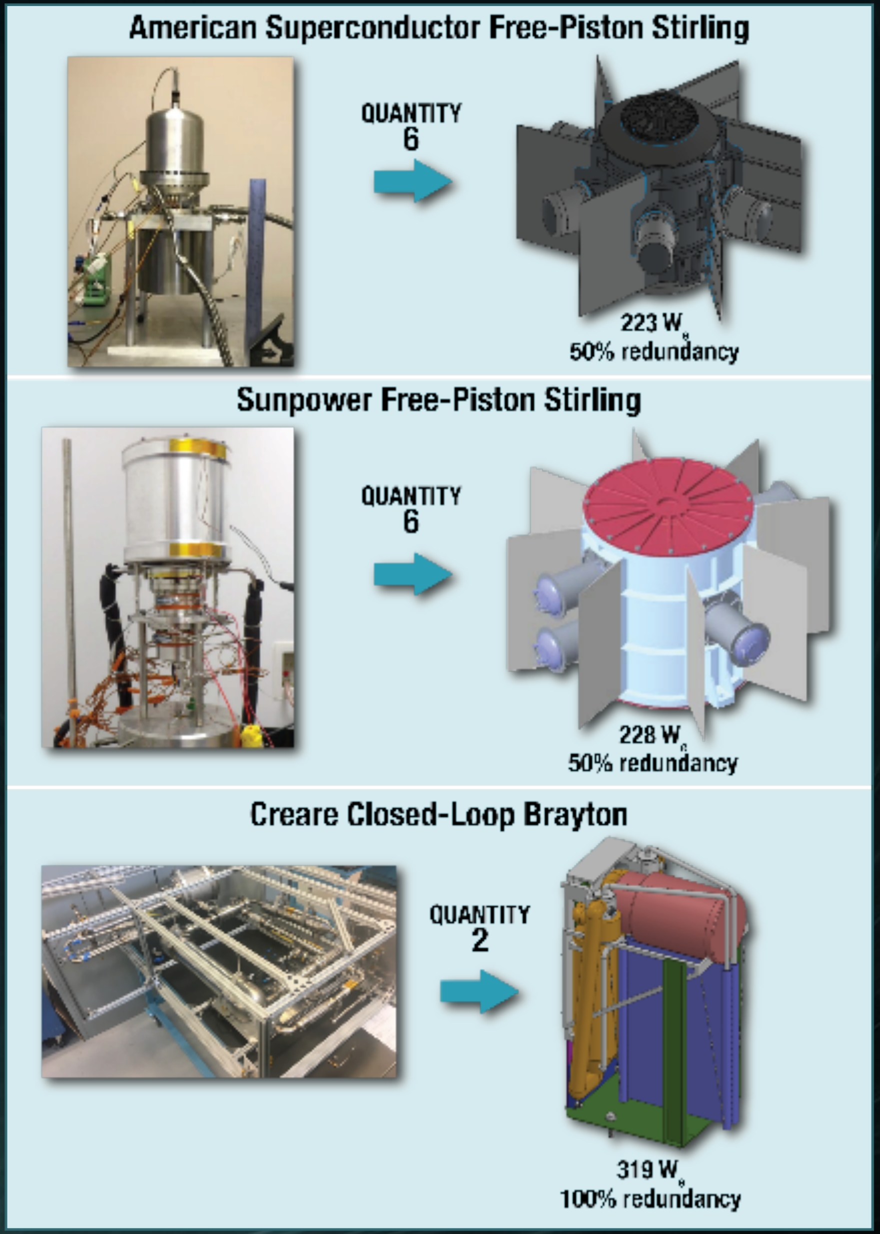
Voyager 1
Sept. 5, 1977–Present
3 MHW RTG: @~158 W_e BOL

Voyager 2
Aug. 20, 1977–Present
3 MHW RTG: @~158 W_e BOL

* U.S. Air Force Mission

Dynamic Radioisotope Power Systems (DRPS)

- DRPS provide multi-mission capability with significantly lower Heat Source consumption and thermal properties that uniquely enable some science missions
- Investment in multiple robust dynamic conversion technologies
  - 2 technologies have multiple ground units that have individually continuously operated for over 14 years without maintenance demonstrating life and low degradation rates
- Initiated DOE flight system design in FY21 with procurement process to select System Integrating Contractor
  - Multi-mission design with protoflight lunar system
  - Current budget provides for PDR and system level brassboard development necessary to prove technology readiness for full protoflight development
- Protoflight unit to target lunar demonstration
  - Demo serves as pathfinder for dynamic conversion which is required for fission-based power designed

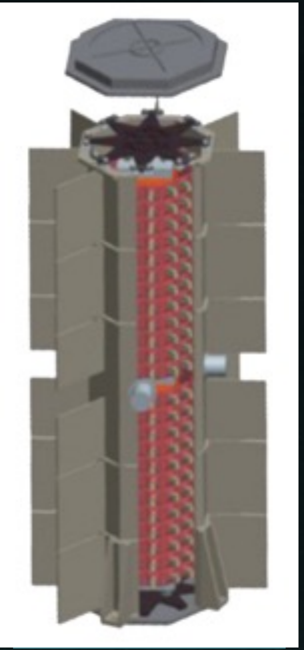


RPS Technology Investments

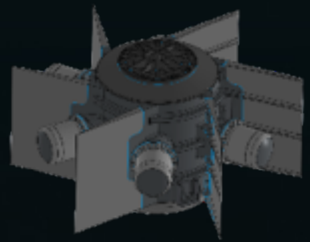
Current System

MMRTG
Curiosity, M2020, *Dragonfly*

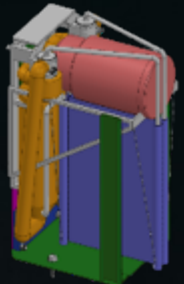
Next Gen RTG
Mod 1



AMSC/
FISC



Creare/
TBC



Sunpower/
SRSC

Simplistic RPS **Decade Analysis** per current CRP

	Current System (MMRTG)	Next Gen RTG Mod 1	AMSC/FISC, Creare/TBC, Sunpower/SRSC
Possible Quantity of Fueled RPS	3 to 4 MMRTG	1.5 to 2 GPHS RTG	4 to 6 DRPS
Possible Power Provided (BOM)	330 to 440 W_e MMRTG	368 to 490 W_e GPHS RTG	964 to 1446 W_e DRPS

Launch Authorization Process

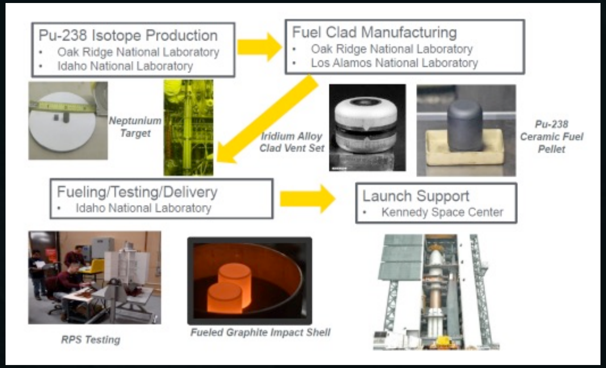
- NSPM-20 replaces the prior standard employed (PD/NSC-25) for U.S. Launch Authorization (8/2019)
- NSPM-20 necessitates update to NASA NPRs
  - Guidelines vary with quantity and form of material planned for use, as well as, with potential radiological risk
  - Updating NPR 8715.3D Chapter 6* "Nuclear Safety Launching of Radioactive Materials" to NPR 8715.y for compliance with NSPM-20
    - Interagency Nuclear Safety Review Board (INSRB)
    - Reporting levels and launch authorization vary based on Tier
    - DOE prepares SAR for NASA RPS missions per NASA/DOE 2016 MOU

Mars 2020 Mission launching from Cape Canaveral Air Force Station, Florida on July 30, 2020

Note: Interim usage of NPI 8715.93 Impacts of NSPM-20 on NASA Nuclear Flight Safety Requirements and Practices June 2020.

Stewardship Results

- Strong DOE/NASA partnership with well exercised processes to support missions and new system development
- Constant Rate Production (CRP)
  - Sized to meet PSD mission needs, reevaluated on a yearly basis with a 10-year sliding window
  - Production rate increases can be accommodated
  - Increasing plutonium (Pu) production
  - Investment in infrastructure to reduce risks
    - Hot Press 4 to be completed by the end of this year
- NASA Mission Support
  - Mars 2020 mission – Provided an MMRTG $13M under budget, 2 months ahead of schedule, and 6 W_e above required power, all during the unprecedented COVID-19 pandemic
  - Dragonfly mission – Supporting MMRTG trades and NEPA
  - DOE holds authority for nuclear activities, similar to NASA technical authority



CRP Supply Chain

Perseverance

Dragonfly

NASA and DOE Ready To Support Decadal Missions

- Constant Rate Production in Place
  - Plutonium-238 heat source production
  - Fueled clad production
  - Maintaining essential infrastructure
  - Capacity in the system
- Power system
  - MMRTG available now for missions
  - GPHS-RTG available late 2020s for missions
  - DRPS TRL 6 by mid-2020s, with funding available late 2020s for missions

Mission Demand Oriented:

- **Decadal Provides the Vision**
- **Congress Provides the Funding**
- **RPS Program and DOE Provides the Fueled Systems**

Committed to Mission Success

The RPS Program has increasingly demonstrated its value to NASA and the space science community.

60th

1961 *Anniversary* 2021

PROUD PAST—STRONG FUTURE

SPACE NUCLEAR POWER AND PROPULSION

RADIOISOTOPE

POWER SYSTEMS PROGRAM

POWER TO EXPLORE

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Radioisotope Power Systems Program

DISCUSSION

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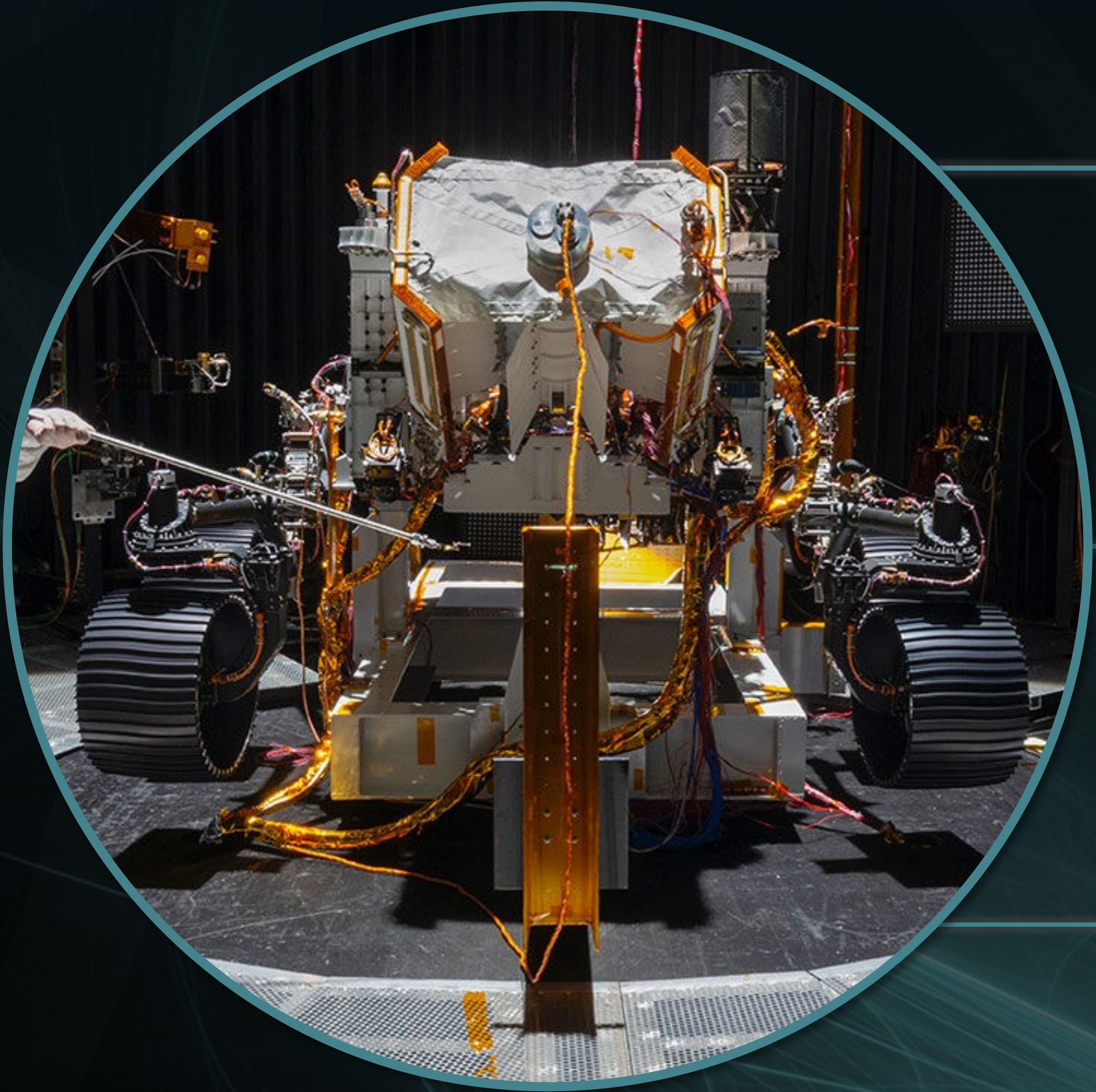
Background for Discussion

- RPS Program is investing in new technology for higher performing RPS to be considered for infusion in next decade
- RPS Program, this decade, is investing in system development
  - Next Gen RTG – bringing back the GPHS-RTG production line
  - DRPS – developing higher efficient robust dynamic conversion-based RPS
- *Current Constant Production Rates (CRP) provided to DOE meet NASA needs in this decade*
  - *Sized to meet PSD mission needs, reevaluated on a yearly basis with a 10-year sliding window*
  - *Yearly Average Rates: 10-15 FC per year and 1.5 kg HS-PuO_2 starting in 2026*
- DOE has designed capacity into CRP and could increase rates at NASA's request – requires additional funding and finite time to reach higher CRP rates

Power to...



EXPLORE

DISCOVER

UNDERSTAND

PEOPLE

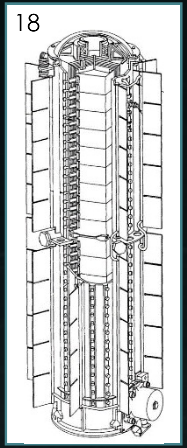
POWER

PRODUCTION

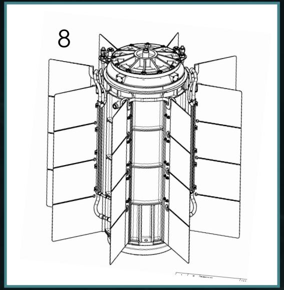
PROGRESS

Performance Comparison

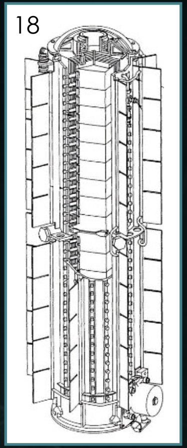
GPHS RTG:
Cassini, Galileo, Ulysses, New Horizons



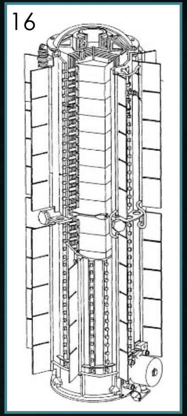
MMRTG:
Curiosity, M2020, *Dragonfly*



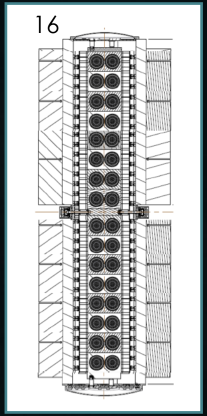
GPHS RTG:
Cassini, Galileo, Ulysses, New Horizons



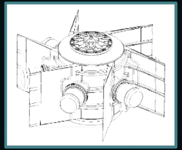
Next Gen RTG Mod 1



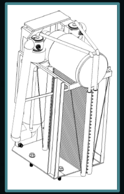
Next Gen RTG Mod 2



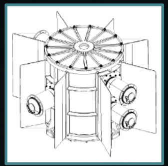
AMSC/FISC



Creare/TBC



Sunpower/SRSC



Parameter	GPHS-RTG	MMRTG	Next Gen Mod 0	Next Gen Mod 1	Next Gen Mod 2	DRPS
P_{BOL} (W_e)	291	110	293	245	400	300 to 400
Mass (kg)	58	44	56	56	56	100 to 200
Q_{BOL} (W_{th})	4410	2000	4500	4000	4000	1500
P_{EODL}, $P=P_0{*}e^{-rt}$ (W_e)	N/A	63	208	177	290	241 to 321
Maximum Average Annual Power Degradation, r (%/yr)	1.54	3.8	1.9	1.9	1.9	1.3
Fueled Storage Life, t (yrs)	2	3	3	3	3	3
Flight Design Life, t (yrs)	16	14	16	14	14	14
Design Life, t (yrs)	18	17	18	17	17	17
Allowable Flight Voltage Envelope (V)	22-34	22-34	22-34	22-36	22-36	22 to 36
Planetary Atmospheres (Y/N)	N	Y	N	N	N	Y
Estimated Launch Date Availability	N/A	Now	2026	2029	2034	2030

Radioisotope Power Systems Program
Technology Goals and Performance Estimates

		System Efficiency	System Degradation Rate
State of the Art (SOA)	MMRTG	6.2% at BOL	3.2%/yr*
RPS Program Technology Goals	10-year Goal	10% at BOL	1.9%/yr
	20-year Goal	20% at BOL	1.4%/yr
RPS Technologies Current Best Estimate (CBE) Predictions and Targets	STM	6.65% at BOL	2.1%/yr*
	Next Gen Mod 2	10% at BOL	Target: 1.9%/yr*
	DRPS-FISC (Stirling)	> 20% at BOL	1.3%/yr
	DRPS-SRSC (Stirling)	> 20% at BOL	1.3%/yr
	DRPS-TBC (Turbo-Brayton)	> 20% at BOL	Target: 1.3%/yr
	SmallSTEP (Stirling)	Target: 20% at BOL	Target: 1.3%/yr
	GHOST	Target: > 15% at BOL	Target: 1.9%/yr*
	JTEC (Ericson)	Target: > 30% at BOL	Target: 1.9%/yr

* Based upon exponential rate law

Notes
- Goals are overarching programmatic goals across all technologies
- RPS Program is refining and updating these goals as needed
- Targets are for lower level TRLs that we have little data to substantiate CBEs
- BOL represents a deep space case, 250 W_e per GPHS

AMSC – American Semiconductor
FISC – Flexure Isotope Stirling Converter
GHOST – Group for the HOlistic Science of Thermoelectrics (GHOST) Task
JTEC – Johnson Thermo-Electrochemical Converter
SmallSTEP – Small Stirling Technology Exploration Power
SRSC – Sunpower Robust Stirling Converter
STM – Skutterudite Technology Maturation
TAPC – ThermoAcoustic Power Converter
TBC – Turbo-Brayton Converter

NSPM-20 Risk-Based Tiered Approval

- Tier I applies when *all* of the following apply:
  - The quantity of radioactive material equals more than and including 1,000 times the "A2 value" and up to and including 100,000 times the "A2 value" established in the International Atomic Energy Agency's (IAEA) current standards for safe transport of radioactive material;
  - Safety analysis finds that there is no credible accident scenario (less than 1 in a million chance) that might result in radiation exposure of 5 rem or greater Total Effective Dose (TED) to any member of the public; and
  - The space nuclear system is not a nuclear reactor.
- Tier II applies when *any* of the following applies:
  - The quantity of radioactive material exceeds 100,000 times the "A2 value" established in the IAEA current standards for safe transport of radioactive material; or
  - Safety analysis finds that the there is a credible accident scenario (greater than or equal to 1 in a million chance) that might result in radiation exposure of 5 rem to 25 rem TED to any member of the public; or
  - The system has potential for nuclear criticality and uses low-enriched uranium fuel.
- Tier III applies when *either* of the following applies:
  - Safety analysis finds that there is a credible accident scenario (greater than or equal to 1 in a million chance) that might result in radiation exposure greater than 25 rem TED to any member of the public; or
  - The system has potential for nuclear criticality using any nuclear fuel other than low-enriched uranium.

Head of Sponsoring Agency Authorizes Launch

POTUS or Delegate Authorizes Launch

RPS Fuel Production and Availability

- Constant Rate Production
  - Department of Energy has reestablished the capability to domestically produce plutoninium-238 in support of RPS.
  - RPS is well positioned to enable future exploration.