1961
1971
1981
1991
2001
2011
2021

National Aeronautics and Space Administration

Department of Energy

RADIOISOTOPE
POWER SYSTEMS PROGRAM

# BALANCING FUTURE NASA RPS MISSION NEEDS WITH THE US Pu-238 SUPPLY

## A View Through 2030


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**Space Power Workshop**
**April 23-26, 2018**

# Outline

- NASA Missions' RPS History
- A Shift in Approach
  - NASA funds the DOE Production Operations
  - Adopting a Constant Rate Production approach
- Future Missions and Possible Future Missions
  - Mars 2020
  - Dragonfly
  - Moon
  - Ice Giants/ New Frontiers 5
- Systems
- Summary

# A LOOK BACK

## THOMAS SUTLIFF

# Radioisotope Power Systems

- Radioisotope Power Systems (RPS) are ideally suited for missions that need autonomous, long-duration power
  - Proven record of operation in the most extreme cold, dusty, dark, and high-radiation environments, both in space and on planetary surfaces.
- RPS provide long-lived power solutions for future Planetary Decadal Science missions
  - Mars 2020 (sample return precursor)
  - Uranus Orbiter/Probe
  - New Frontiers (Ocean-Worlds, Saturn, Lunar)
- RPS technologies offer potential to serve a wide range of missions from Small-sat/Cube-sat to Flagship-class Science (1-1000 $W_e$)
  - Thermoelectric (Pb-Te/TAGS; Skutterudite)
  - Dynamic (Stirling)
  - Radioisotope Heater Units
- RPS Program has an established relationship with DOE and has processes in place to work effectively

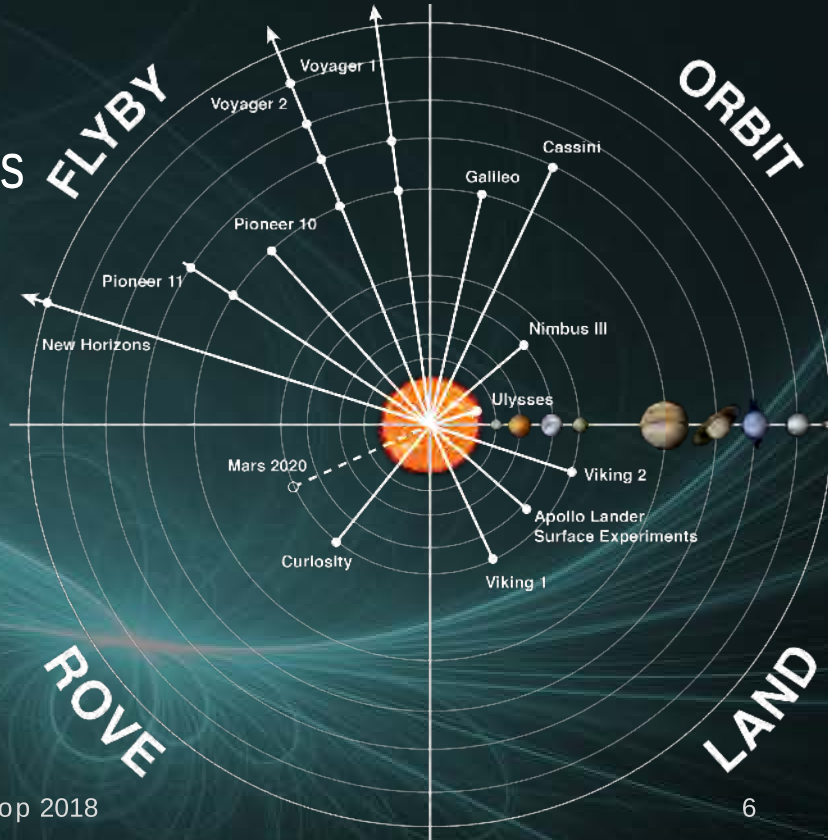
**RPS have successfully powered NASA Missions for over 40 years and continues to serve the needs of NASA in its exploration of the Solar System**

# NASA RPS Flight History by Type

| RPS Type | # Units | Missions (Launch Year) |
|---|---|---|
| SNAP-19 | 13 | Nimbus III (69)<br>Pioneer 10 (72)<br>Pioneer 11 (73)<br>Viking 1 & 2 (75) |
| SNAP-27 | 6 | Apollo 12-17 (69-72) |
| MHW-RTG | 10 | [ LES 8 & 9 (76) ]<br>Voyager 1 & 2 (77) |
| GPHS-RTG | 7 | Galileo (89)<br>Ulysses (90)<br>Cassini (97)<br>New Horizons (06) |
| MMRTG | 1 | MSL (11) |

# System Commonalities and Differences

- Fuel type(s)
  - Pu-238 based fuels
  - Various forms of oxide
  - Encapsulation based on improving safety basis
- Energy conversion and system technologies
  - Thermoelectric conversion
  - Vacuum based and atmospheric
- NASA Mission Characteristics
  - Flyby (5 missions)
  - Orbit (4 missions)
  - Land (8 missions)
  - Rove (1 mission)



# CONSTANT RATE PRODUCTION OVERVIEW

## MARY MCCUNE

# DOE RPS Supply Chain (1/5)

**Pu-238 Isotope Production**
- Oak Ridge National Laboratory
- Idaho National Laboratory

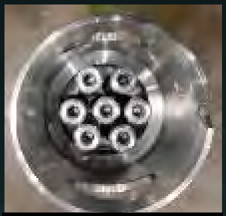
**Fueled Clad Manufacturing**
- Oak Ridge National Laboratory
- Los Alamos National Laboratory

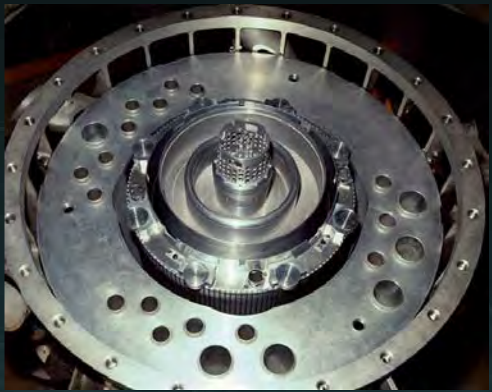
**Fueling/Testing/Delivery**
- Idaho National Laboratory

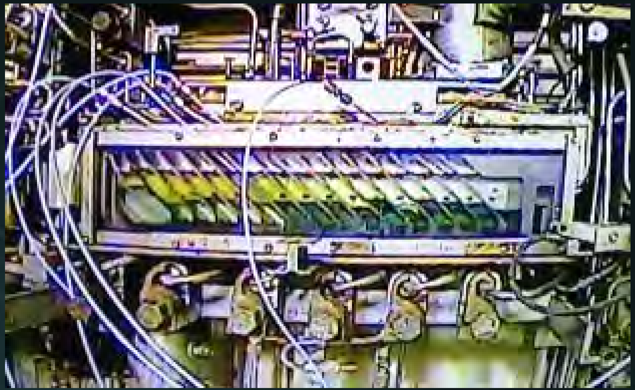
**Launch Support**
- Kennedy Space Center

# DOE RPS Supply Chain (2/5)

- **Pu-238 Production**
  - Oak Ridge National Laboratory
  - Idaho National Laboratory







# DOE RPS Supply Chain (3/5)

- **Fueled Clad/Heat Source Manufacturing**
  - Oak Ridge National Laboratory
  - Los Alamos National Laboratory
  - Idaho National Laboratory





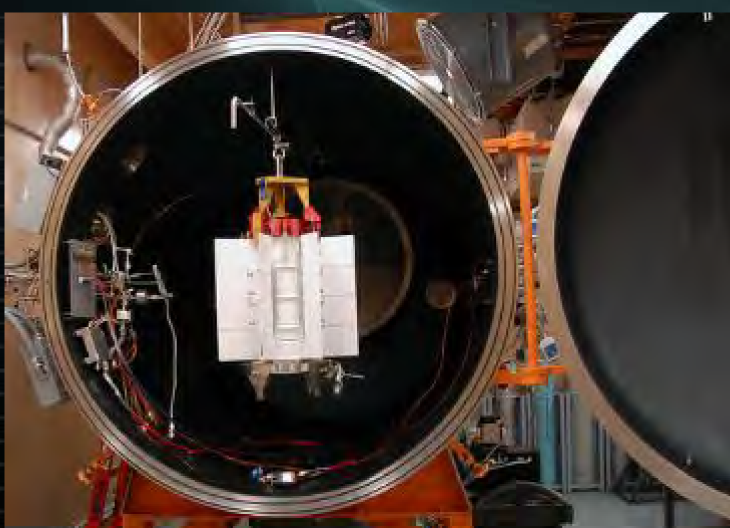




# DOE RPS Supply Chain (4/5)

- **Fueling/ Testing/ Delivery**
  - Idaho National Laboratory



# DOE RPS Supply Chain (5/5)

- **Launch Support**
  - Kennedy Space Center

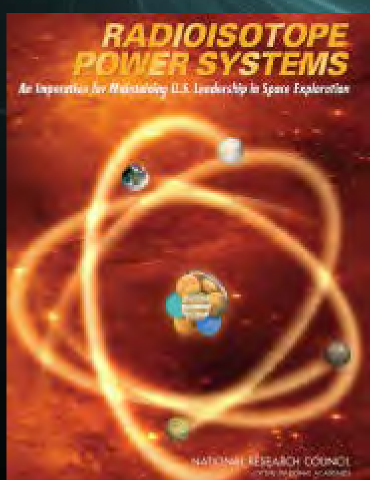


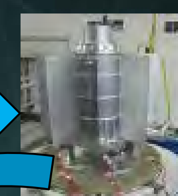




# Re-Established Plutonium Production – New Pu-238!!

- December 2015, ORNL successfully completed the target fabrication ⇨ irradiation ⇨ separation process yielding a 50 g quantity of new Pu-238
- Samples were converted into plutonium oxide (HS-$PuO_2$) and sent to LANL
  - Chemical composition was found to meet (or be better than) specification for use in the flight-standard fueled clads
  - Some material sent to LANL has been blended into heat source clads for the upcoming Mars 2020 Mission's MMRTG



# DOE Constant Rate Production (CRP)

- Past production practice was mission specific campaigns
- CRP leverages DOE standard campaign model providing flexibility for NASA missions
  - Reduces mission risk
  - **Reduced Mission Costs by ~$37 M (25%)**
- By fiscal year 2019
  - Maintain average production rate of 400 g/y
- By fiscal year 2021
  - Add additional irradiation capability at the Advanced Test Reactor (ATR) for redundancy
  - Maintain 10-15/year constant-rate of fueled clads
- By fiscal year 2025
  - Maintain average production rate of 1.5 kg/y with surge capacity to ~2.5 kg/y (as funded)
  - Completed modernization campaign at LANL

*Newly produced plutonium-238*

*Aqueous Processing Line at Los Alamos*

*10-15 fueled clads/year*

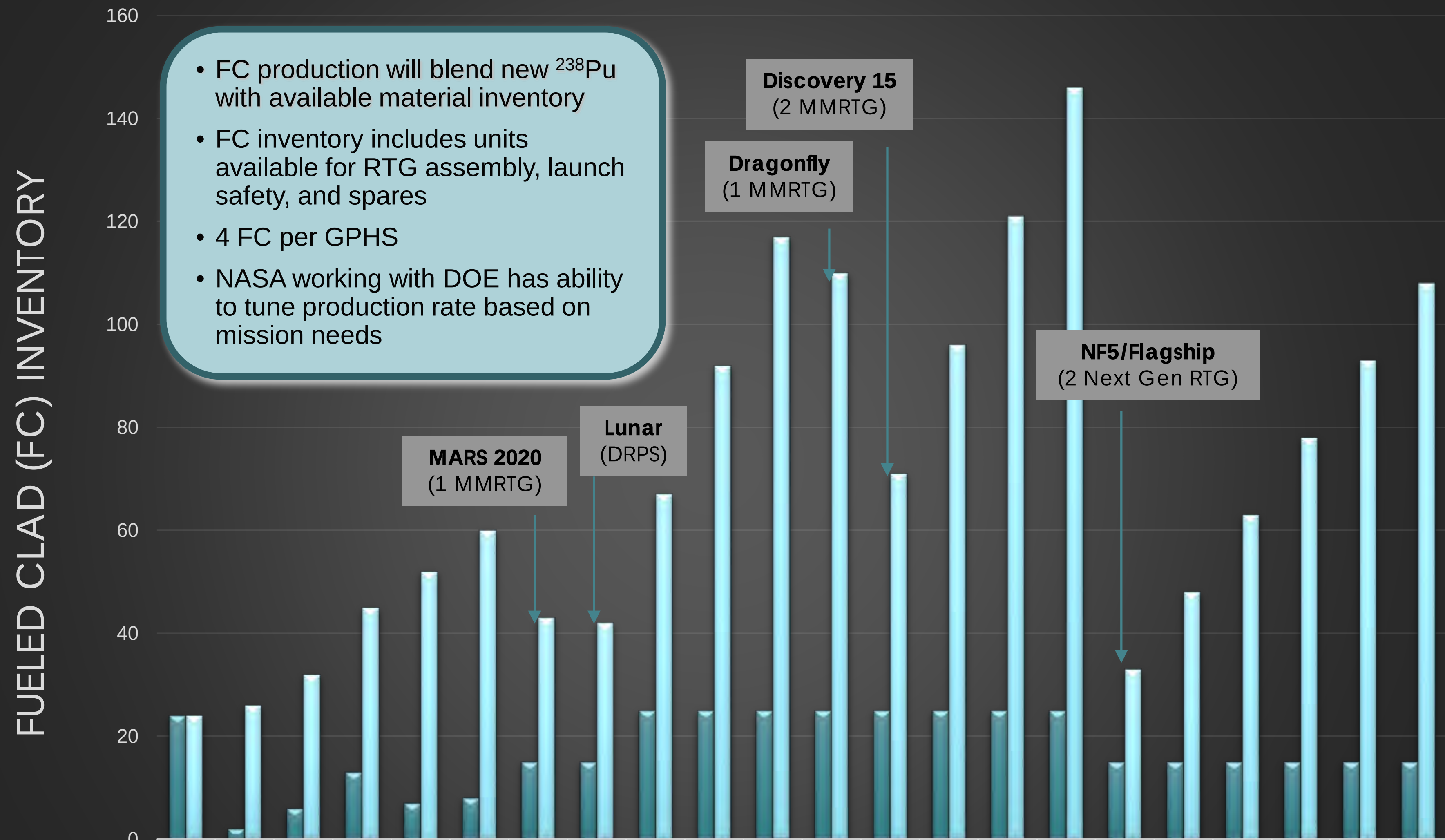
*(4 needed for a GPHS)*

**CONSTANT RATE PRODUCTION REDUCES MISSION RISK AND REDUCES COSTS BY 25%**

# NASA Set-Aside Plutonium vs Planetary Requirements

## Current Projections with Constant Production Rates

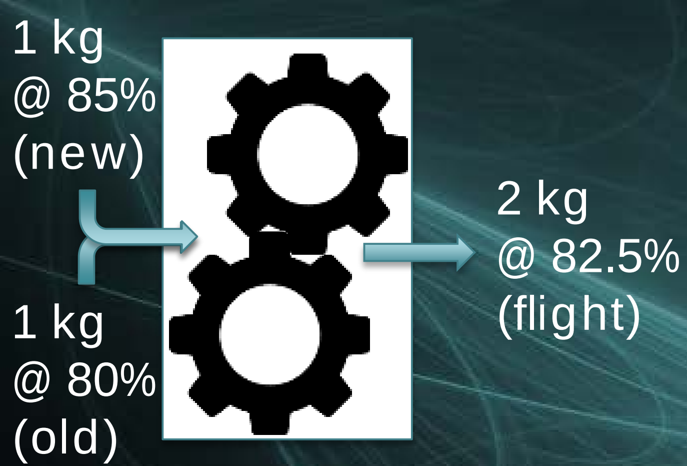
- FC production will blend new $^{238}Pu$ with available material inventory
- FC inventory includes units available for RTG assembly, launch safety, and spares
- 4 FC per GPHS
- NASA working with DOE has ability to tune production rate based on mission needs

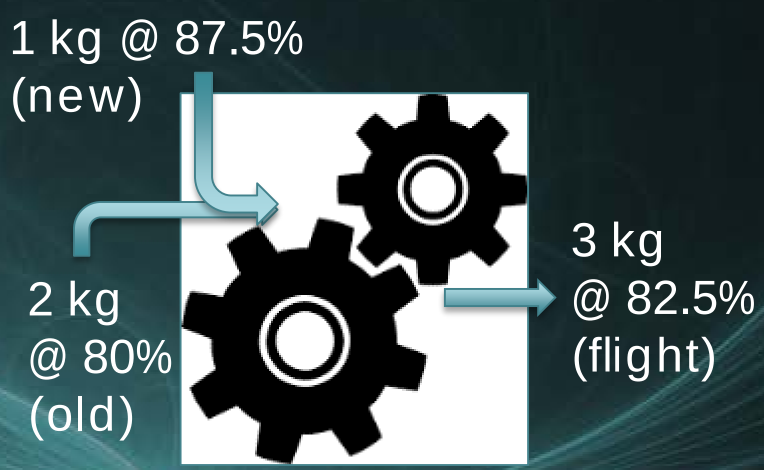



| | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27 | FY28 | FY29 | FY30 | FY31 | FY32 | FY33 | FY34 | FY35 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FC Production | 24 | 2 | 6 | 13 | 7 | 8 | 15 | 15 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 15 | 15 | 15 | 15 | 15 | 15 |
| FC Inventory | 24 | 26 | 32 | 45 | 52 | 60 | 43 | 42 | 67 | 92 | 117 | 110 | 71 | 96 | 121 | 146 | 33 | 48 | 63 | 78 | 93 | 108 |

# Blending of HS-$PuO_2$

- Nominal flight assay goal [Pu-238/Pu(total)] is ~82.5% in each fueled clad
- Below specification fuel can be blended with newly produced heat source material by LANL
- Blending ratios will vary, and will depend on starting assays



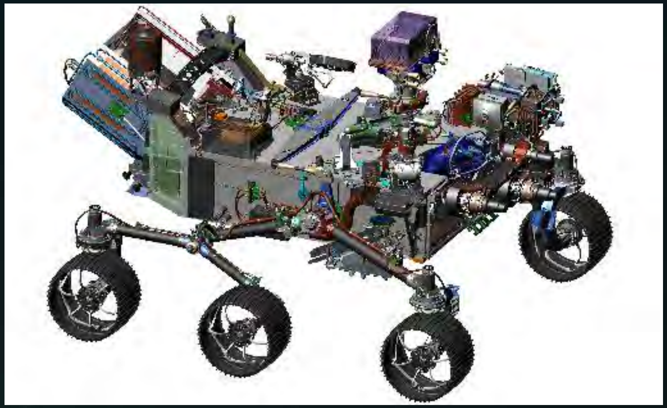




*An illustrative example*

# A LOOK TO THE FUTURE
# MISSIONS AND SYSTEMS

# Mars 2020

- Versus Curiosity rover:
  - Design philosophy is “build to print”
  - Most significant difference would be new science instruments and technology experiments



- Power:
  - Baseline power (as with Curiosity) is RPS-based
  - Two flight MMRTGs (F2, F3) have been acquired by the RPS Program subsequent to Curiosity’s use of the first MMRTG

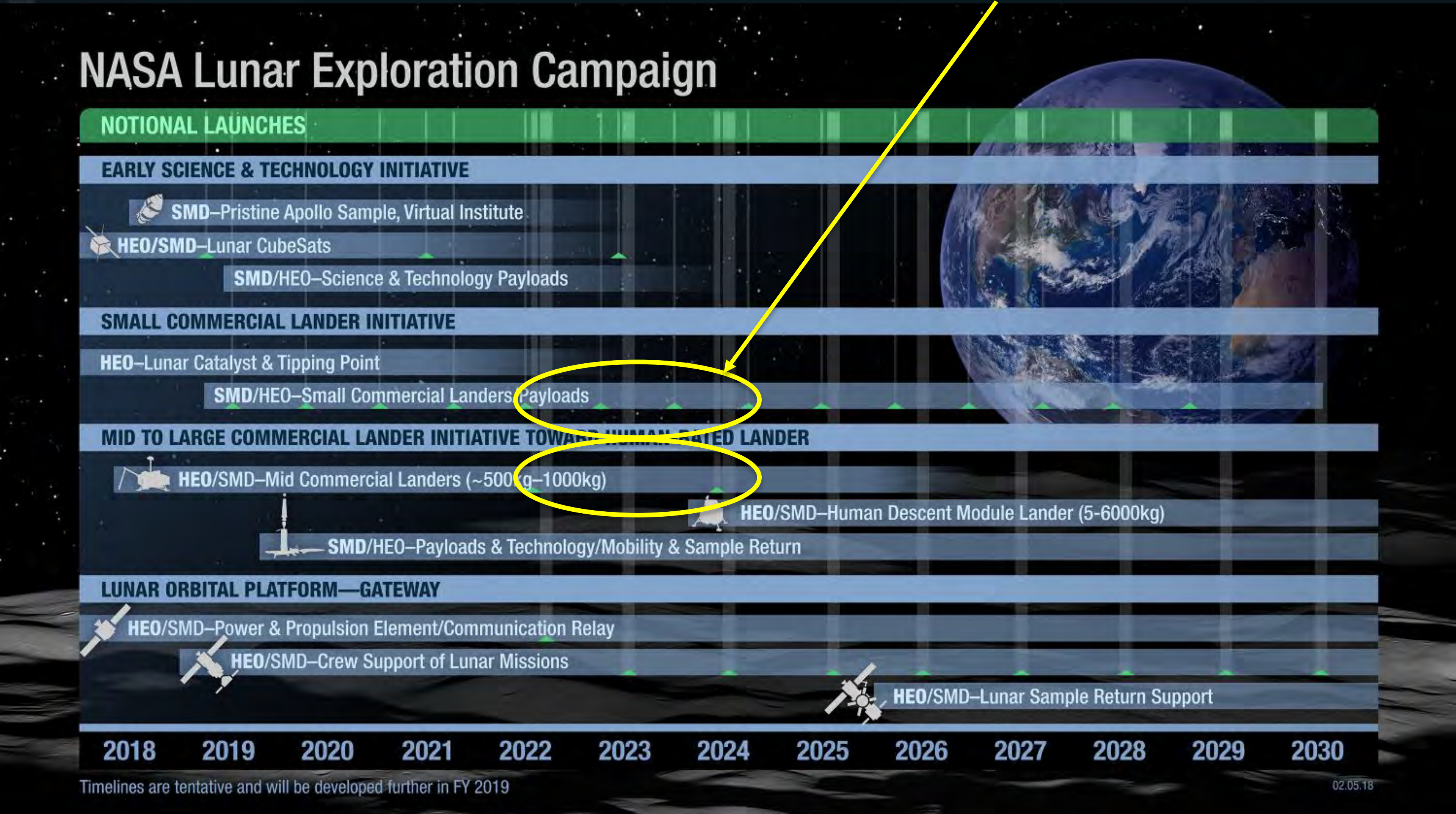
# What makes a planet or moon habitable?
# What chemical processes led to the development of life?

- Titan is an ideal destination to answer these questions because it has the key ingredients known to be necessary for life:
  - **Energy:** Sunlight
  - **Organic material:** Abundant carbon and more complex organics
  - **Liquid water:**
    - Melting of Titan's ice crust at sites like impact craters and cryovolcanoes
    - Potential for surface organics to be transported to the vast ocean hidden beneath the crust
- An Earth-like world but with liquid methane rain, rivers, lakes & seas
  - Methane might also support development of biological systems
- Titan is an **ocean world** laboratory to investigate primitive chemistry and to search for biosignatures

**Titan's atmosphere and low gravity make it easier to fly there than on Earth: Dragonfly can explore *dozens* of sites *tens to hundreds of miles apart***

Led by Dr. Elizabeth Turtle at APL, Dragonfly would arrive at Titan in 2034 and explore for over 2 years, making detailed measurements of surface composition, the atmosphere, and seismic activity, as well as taking images.

Possible RPS application



# Discovery AO Announcement

- NASA's Planetary Science Division announced in March 2018 that the science community will be able to propose mission concepts that could use RPS in response to the upcoming NASA Discovery 2019 AO.

- Proposers will be able to consider the use of up to 2 MMRTGs, if that would enable or significantly enhance the ability of their mission concept to meet its scientific and/or operational goals.
  - The costs to be borne by proposers for using MMRTGs, including the NEPA process and the required nuclear launch safety approval process.

- After RPS were initially not included in NASA planning for Discovery 2019, interest expressed by the community in potentially using RPS for it, combined with further analysis by NASA and DOE, resulted in a revised position.
  - Analysis found that additional MMRTGs could be built to meet the mission schedule, and that sufficient heat source plutonium would be available to fuel the generators.

- A Draft Discovery AO is slated for release in September 2018. The selected mission would be targeted for launch in the 2025-2026 timeframe.

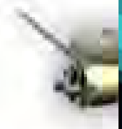
## What changed?

- Prior to selection of New Frontiers-4, Step 1 awardees, Discovery was precluding use of RPS.

- Subsequent to Dragonfly (needing only 1 MMRTG), HQ announced that up to two MMRTGs could be available for the Discovery 2019 AO

# Uranus / Neptune

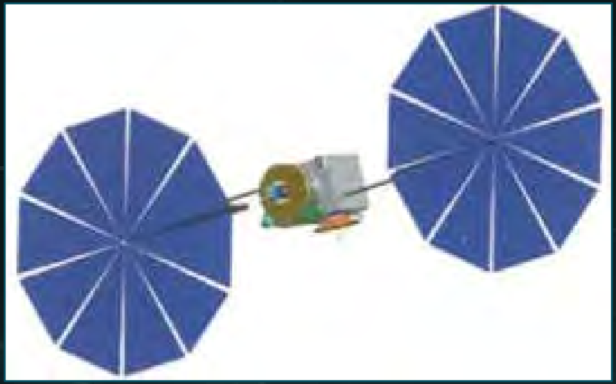

Table 1-1. Mission concept analysis summary.

| |  |  |  |  |
|---|---|---|---|---|
| Case Description | Neptune Orbiter with probe and ~50 kg science payload. Includes SEP stage for inner solar system thrusting. | Uranus Flyby with probe and ~50 kg science payload. Chemical only mission. | Uranus Orbiter with probe and ~50 kg science payload. Chemical only mission. | Uranus Orbite… probe, but wi… science pa… Chemical onl… |
| Science | Highest priority plus additional system science (rings, sats, magnetospheres) | Highest priority science (interior structure and composition) | Highest priority plus additional system science (rings, sats, magnetospheres) | All remote … objectives |
| Payload | 3 instruments* + atmospheric probe | 3 instruments* + atmospheric probe | 3 instruments* + atmospheric probe | 15 instruments** |
| Payload Mass MEV (kg) | 45 | 45 | 45 | 170 |
| Launch Mass (kg) | 7365 | 1524 | 4345 | 4717 |
| Launch Year | 2030 | 2030 | 2031 | 2031 |
| Flight Time (yr) | 13 | 10 | 12 | 12 |
| Time in Orbit (yr) | 2 | Flyby | 3 | 3 |
| Total Mission Length (yr) | 15 | 10 | 15 | 15 |
| RPS use/ EOM Power | 4 eMMRTGs/ 376W | 4 eMMRTGs/ 425W | 4 eMMRTGs/ 376W | 5 eMMRTGs/ 470W |
| LV | Delta IVH + 25 kW SEP | Atlas V 541 | Atlas V 551 | Atlas V 551 |
| Prop System | Dual Mode/NEXT EP | Monopropellant | Dual Mode | Dual Mode |

**includes Narrow Angle Camera, Doppler Imager, Magnetometer **includes Narrow Angle Camera, Doppler Imager, Magnetometer, Vis-NIR Mapping Spec., Mid-IR Spec., UV Imaging Spec., Plasma Suite, Thermal IR, Energetic Neutral Atoms, Dust Detector, Langmuir Probe, Microwave Sounder, Wide Angle Camera*

# New Frontiers Focused Missions

COMET SURFACE SAMPLE RETURN



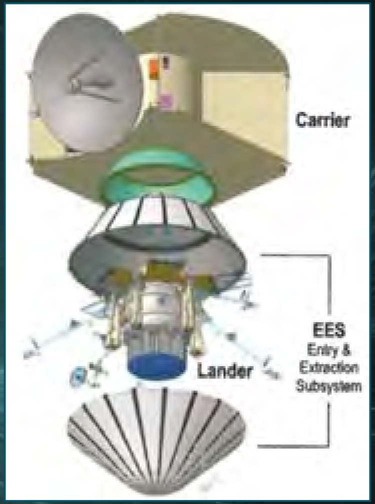
LUNAR SOUTH POLE AITKEN BASIN SAMPLE RETURN

TROJAN TOUR & RENDEZVOUS

SATURN PROBES

OCEAN WORLDS (TITAN AND ENCELADUS)

VENUS IN-SITU EXPLORER




*Courtesy J. Green (HQ); Cassini images*

# Possible Future RPS

- enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG)
  - Retrofit the MMRTG with higher efficient thermoelectric (TE) couples
  - Midway through Technology Maturation Phase
- Next Generation RTG (Next Gen)
  - In-house TE maturation efforts
  - RFI followed by RFP for system concept and technology maturation long-pole plan
  - Initial planning phase
- Dynamic RPS (DRPS)
  - SOA assessment - complete
  - Requirements definition - **complete**
  - Multiple industry, multiple conversion technology contracts – **imminent**

| Parameter | MMRTG | eMMRTG | Next Gen | DRPS |
|---|---|---|---|---|
| TRL | 9 | 3 | 1-3 | 3-4 |
| Potential Flight Readiness Target Date | 2009 | 2022 | 2028 | 2026 |
| $P_0$ - BOL (We) | 110 | 148 | 400-500 | 200-500 |
| Efficiency - $P_0/Q*100$ (%) | 5.50% | 7.40% | 10-14% | 20-25% |
| Specific Power - $P_0/m$ (We/Kg) | 2.4 | 3.3 | 6-8 | 4-6 |
| Q - BOL (Wth) | 2000 | 2000 | 4000 | 1000-2000 |
| Average annual power degradation, r (%/yr) | 4.8% | 2.5% | 1.9% | 1.3% |
| $P_{BOM}$ - $P=P_0*e^{-rt}$ (We) | 110 | 137 | 375-470 | 195-485 |
| Fueled storage life, t (years) | 3 | | | |
| $P_{EODL}$ - $P=P_0*e^{-rt}$ (We) | 49 | 80 | 290-360 | 170-420 |
| Flight Design Life, t (yrs) | 14 | | | |
| Design Life, t (yrs) | 17 | | | |
| Allowable Flight Voltage Envelope (V) | 22-36 | 22-34 | | |
| Planetary Atmospheres (Y/N) | Y | Y | N | Y |

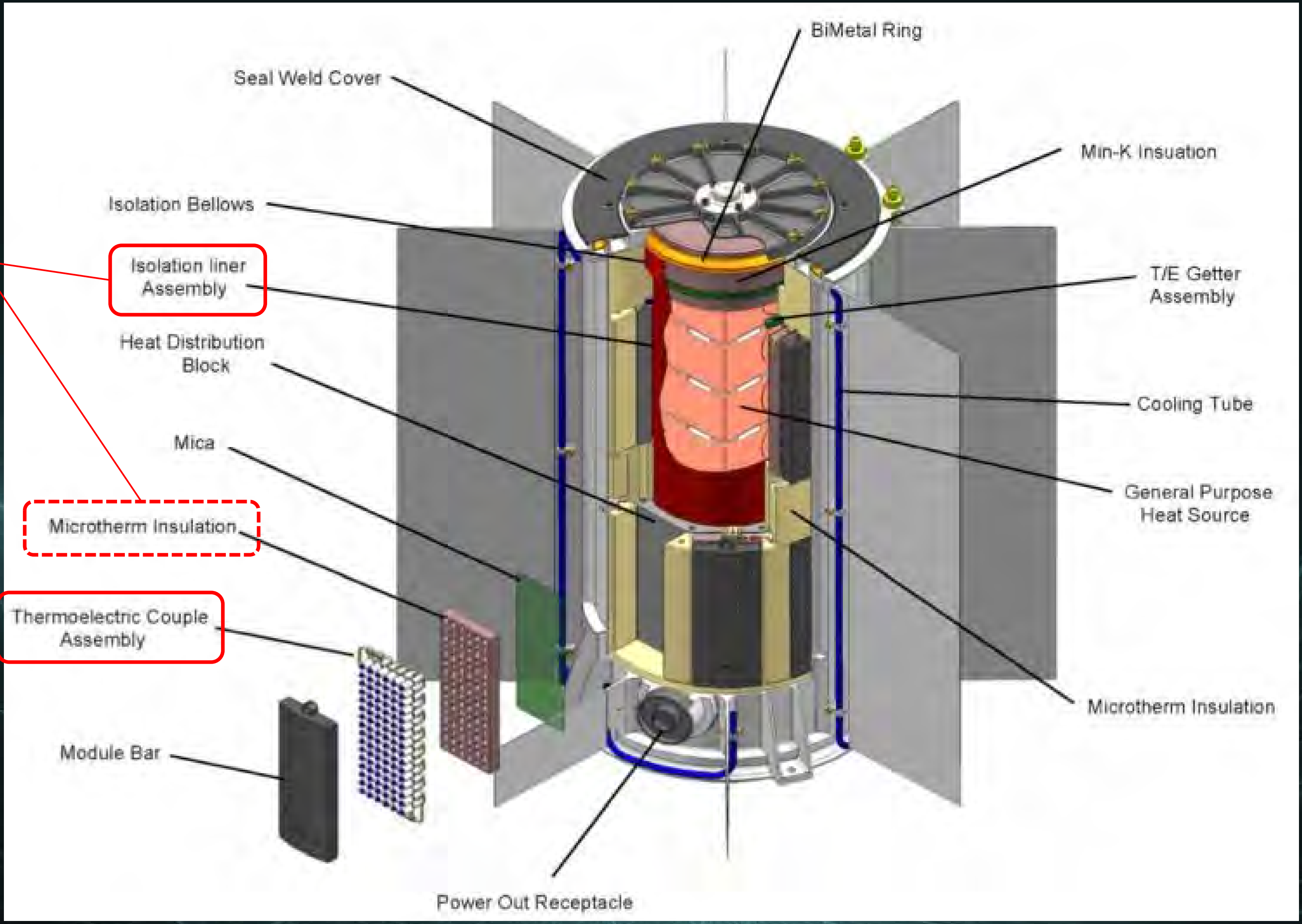
# eMMRTG: What is being enhanced?

- Dashed red box: Enhancements under consideration
- Solid red box: Known enhancements

Engineering:
- emissivity change to liner,
- substitute insulation

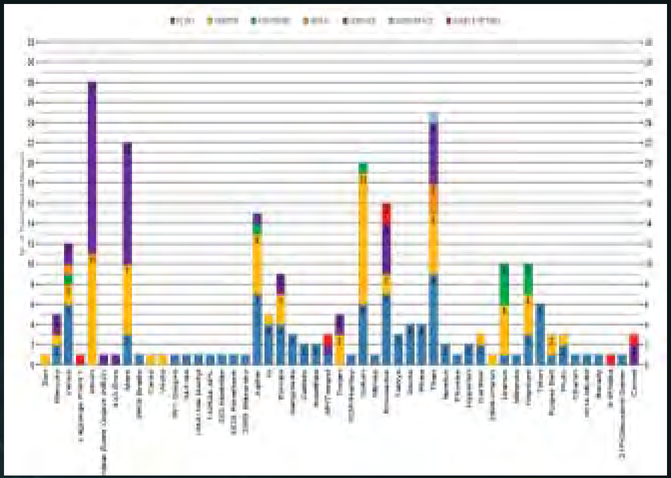
Changes needed to MMRTG

New Technology: Substitute SKD thermoelectric couples

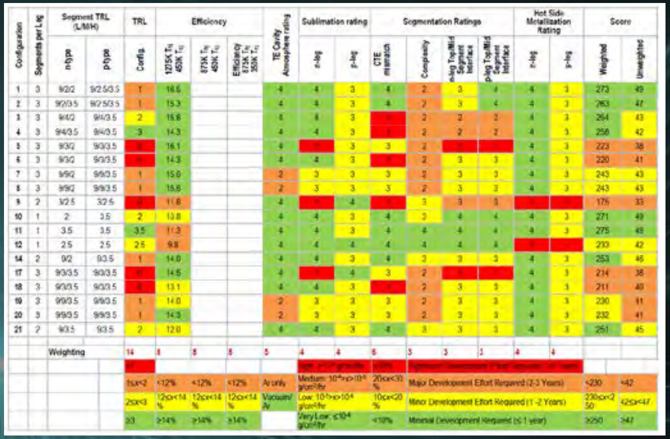


# Next-Gen RTG

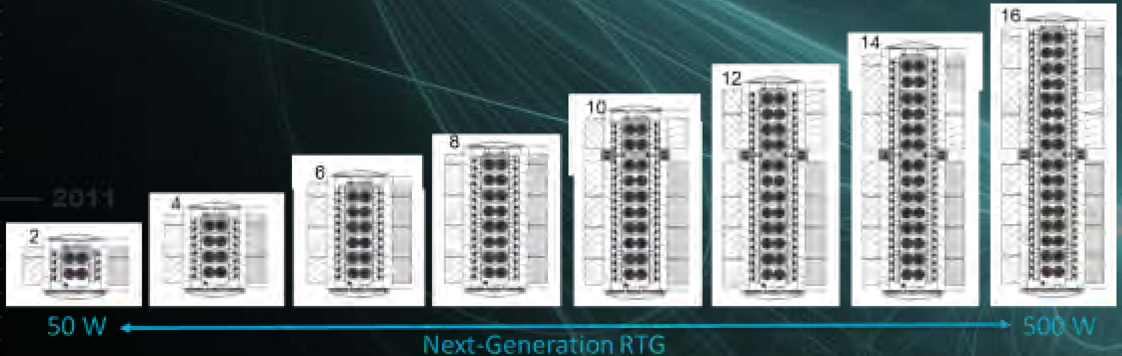
- Conducted Mission/System study to determine the characteristics of a Next-Generation RTG that would "best" fulfill Planetary Science Division (PSD) mission needs.
- Developed *new* RTG Concepts:
  - Vacuum Only
    - Segmented (TECs)
    - Cold Segmented
    - Segmented-Modular
    - Cold Segmented-Modular
  - Vacuum and Atmosphere
    - Hybrid Segmented-Modular
    - Cold Hybrid Segmented-Modular



249 Mission Studies in database

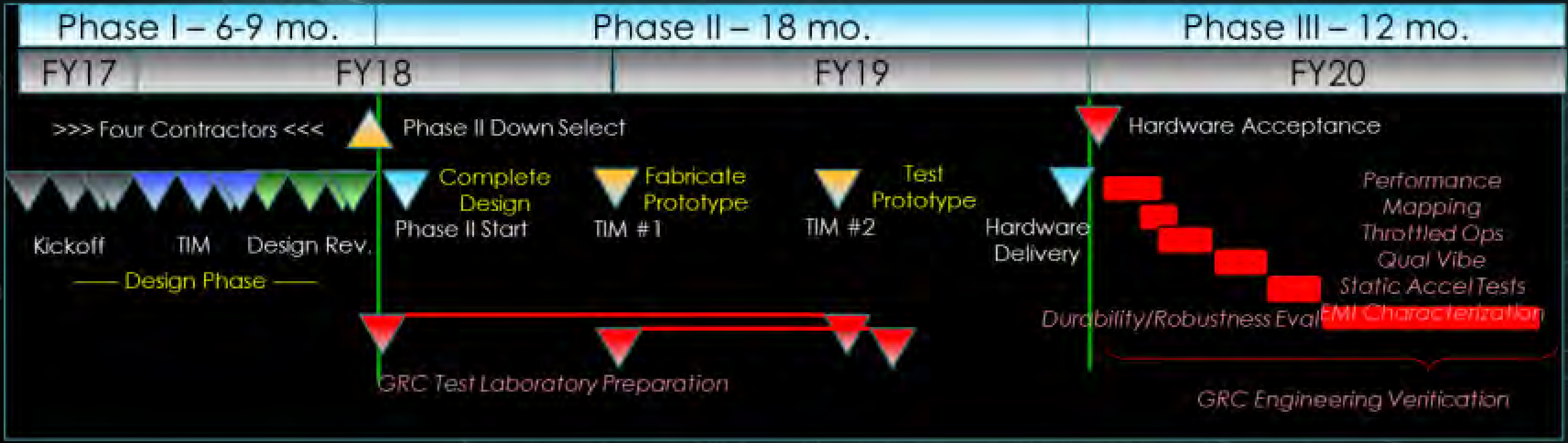



67 Candidate TE Technologies



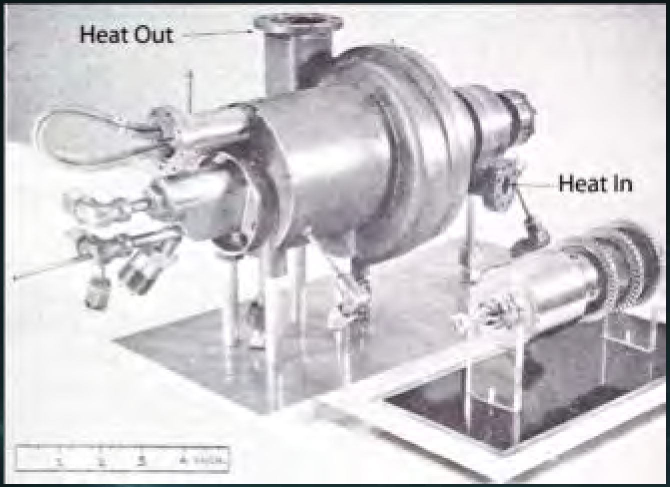
# Dynamic Conversion: Plan and Schedule

- In the context of developing a 200-500 $W_e$ RPS determine the development readiness and risk associated with dynamic power conversion technologies
- Key conversion technology evaluation characteristics
  - Reliability
  - Robustness
  - Manufacturability
  - Life-cycle and sustainability costs
  - Performance
- Benefits Fission Power Systems development

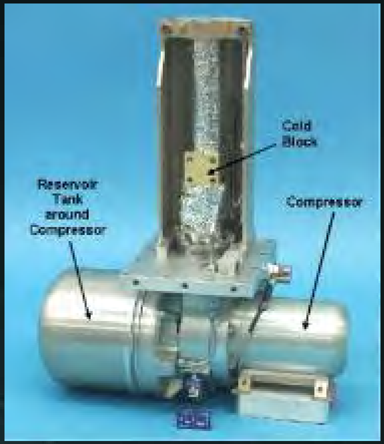


# Dynamic Conversion: 4 Contracts

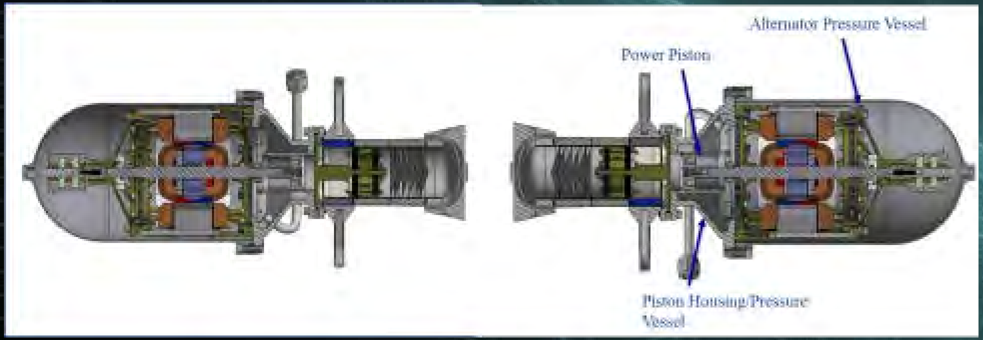
**Creare:** Turbo-Brayton




**Northrop Grumman:** ThermoAcoustic Power Convertor (TAPC)



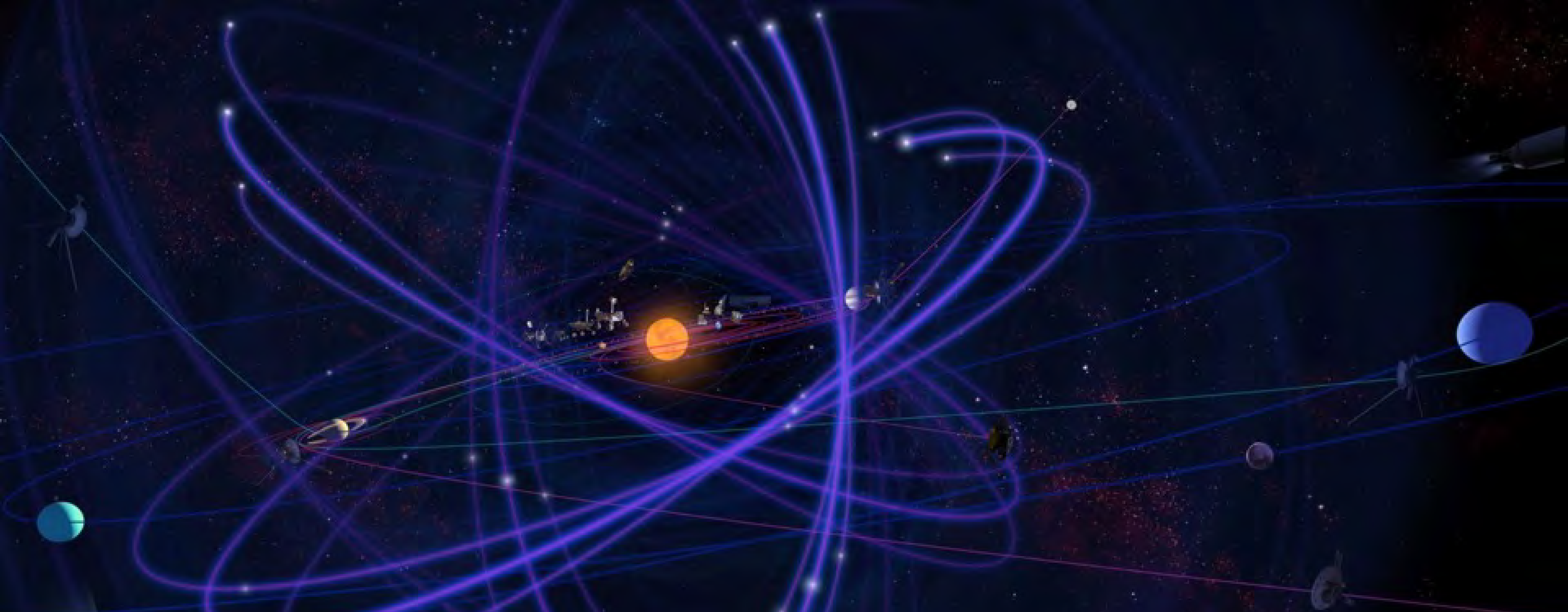

**ITC:** Free-Piston Stirling Engine (FPSE) Flexure




**Sunpower:** FPSE Gas Bearing

# RPS Program Summary

- RPS Program and DOE working together to provide NASA a robust, end-to-end program capability
  - Strong NASA & DOE partnership
  - NASA is
    - Planning for, baselining and implementing exploration missions using radioisotope power
    - Investing in systems and capabilities to ensure mission success
  - DOE is
    - Committed to supporting NASA nuclear missions
    - Actively transforming its customer relationship with NASA to ensure the deliveries of RPS and RHUs
    - Established singular point of contact for all nuclear missions
  - Constant Rate Production
    - Significant cost reductions realized for missions
    - Plutonium Production
      - End-to-End demonstration complete
      - Focused on increasing production rate in phased approach



## *Power to Explore*

https:// rps.nasa.gov