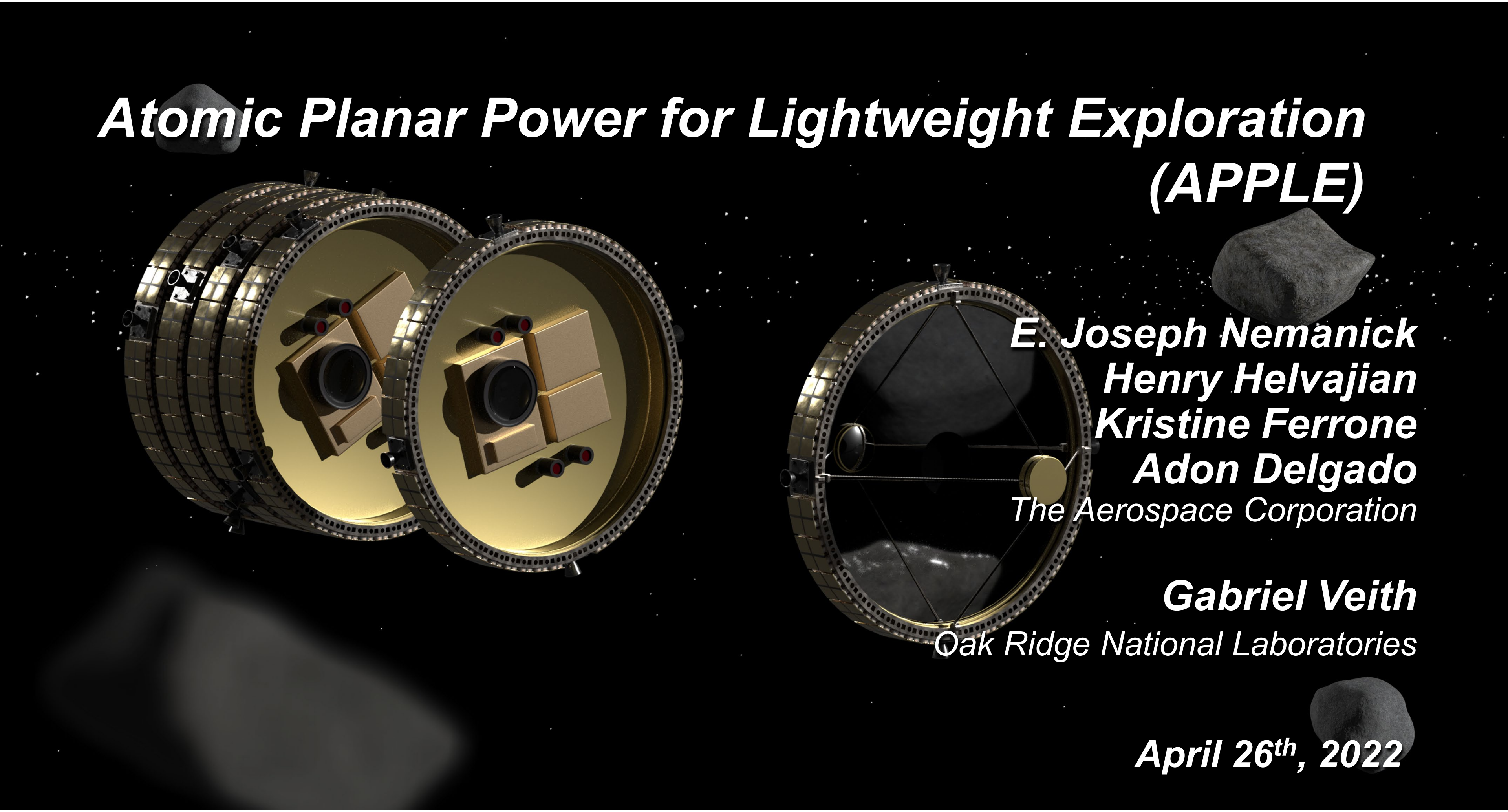

# *Atomic Planar Power for Lightweight Exploration (APPLE)*

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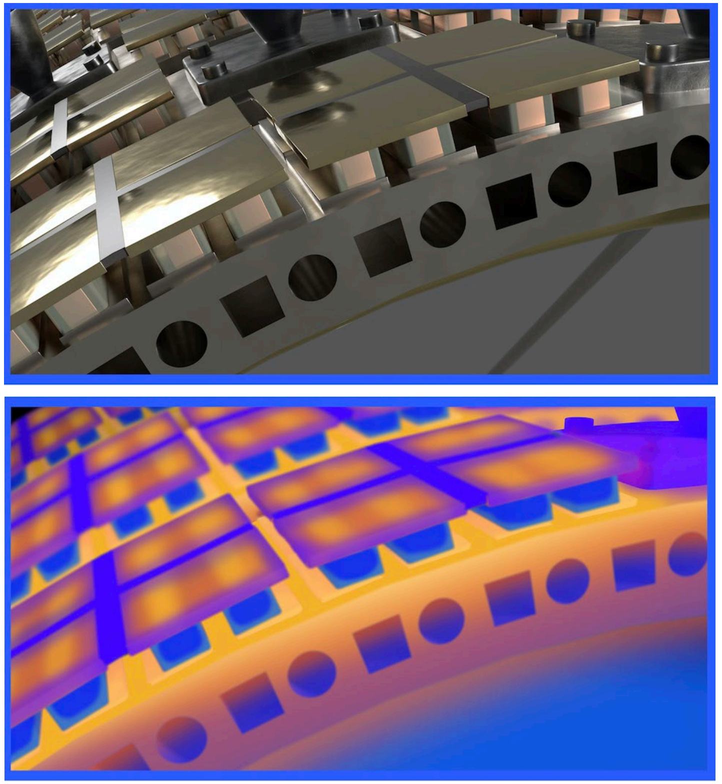
# APPLE

*A lightweight, modular isotope power and battery design.*

- For power in the reaches of the solar system beyond Mars spacecraft use radioisotope thermoelectric generation (RTG) system, like the Multi-mission RTG (MMRTG) of GPHS-RTG. But these large, cylindrical systems are heavy and inefficiently generate power and utilize waste heat.
- The Atomic Planar Power for Lightweight Exploration (APPLE) is an efficient, modular spacecraft power architecture that merges the extensive heritage of radioisotope power generation with a radiation-hard battery in a robust modular system which can enable a wide range of spacecraft and rover design.
- A modular power architecture with small units will open up the design space for deep space bus by enabling power designs to fit the mission for any vehicle shape or size, from 10’s of Watts to kilowatts.

APPLE tiles covering a spacecraft surface



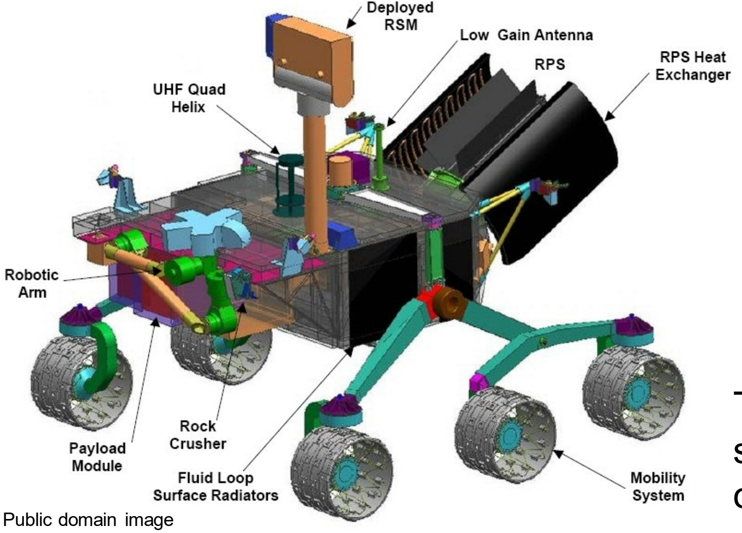
•APPLE can be distributed over the vehicle surface.

•APPLE efficiently utilizes the waste heat to warm the vehicle through multiple power modules.

# Deep Space Power System Needs

- Existing spacecraft that need power for missions with low solar irradiance, such as Mars and beyond, or on long duration rovers typically use radioisotope thermopower generators (RTGs) for power. These systems can use the decay of unstable isotopes such as $^{238}$Pu, $^{90}$Sr, or $^{241}$Am to generate electricity through the radiation of heat to the environment through thermoelectrics, thermophotovoltaics, Brayton engines, or others.

- These systems have traditionally been large, monolithic systems, such as the MultiMission RTG (MMRTG, 125 $W_e$) or the GPHS-RTG (300 $W_e$). These monolithic systems have several issues that place design constraints on the application, including a large amount of heat to be dissipated from a small area, a minimum mission size, and limitations in the vehicle where the RTG can be placed.



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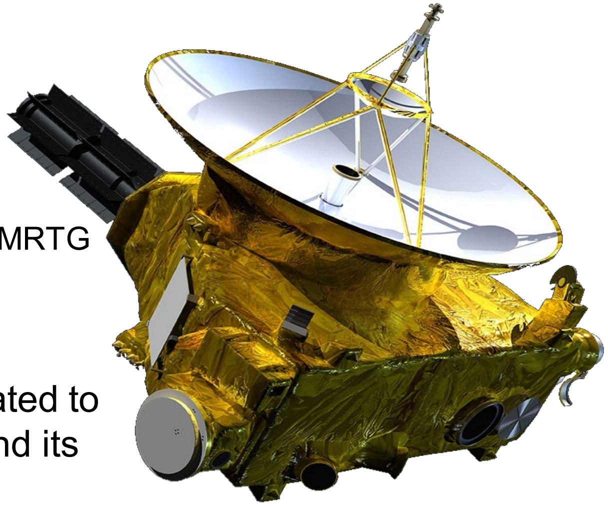
MSL has its MMRTG hanging off the back

New Horizon has its MMRTG hanging out the side

The majority of the heat is dissipated to space, leaving the vehicle to spend its own power to heat the vehicle.



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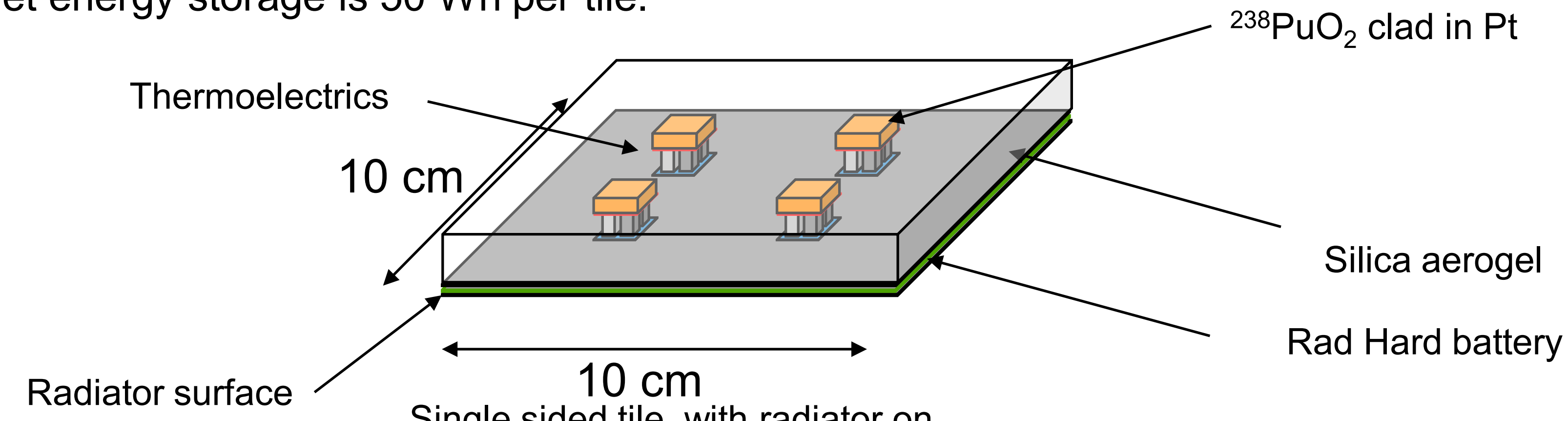
***Smaller spacecraft can go farther, faster, but needs smaller power systems***

# APPLE Tile Concept

- 1.2 $W_e$ tile, using four 1 x 1 x 0.6 cm $^{238}PuO_2$ heat sources, and existing TAGS/PbSnTe-PbTe thermoelectric materials. Total thickness of tile will be ~1.7 cm.
    - Most of the volume of the tile is aerogel and MLI, lightweight multilayer insulation, and adds very little mass.
    - Targeting up to 10% efficient conversion of heat to usable electricity.
    - Up to 14 W thermal available for spacecraft heating per tile.

- The battery is between the radiator and the insulation, ensuring an even, safe temperature for the battery.
    - Battery is exposed to external radiation such as solar flares and cosmic radiation.

- Estimated energy density for a tile is 60 g/$W_e$, a 10x improvement over the MMRTG.
- Target energy storage is 50 Wh per tile.

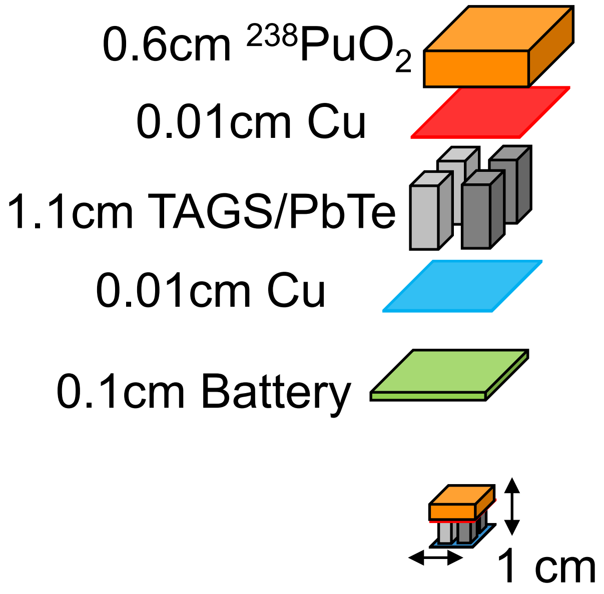


Single sided tile, with radiator on bottom and radioisotope towards top.

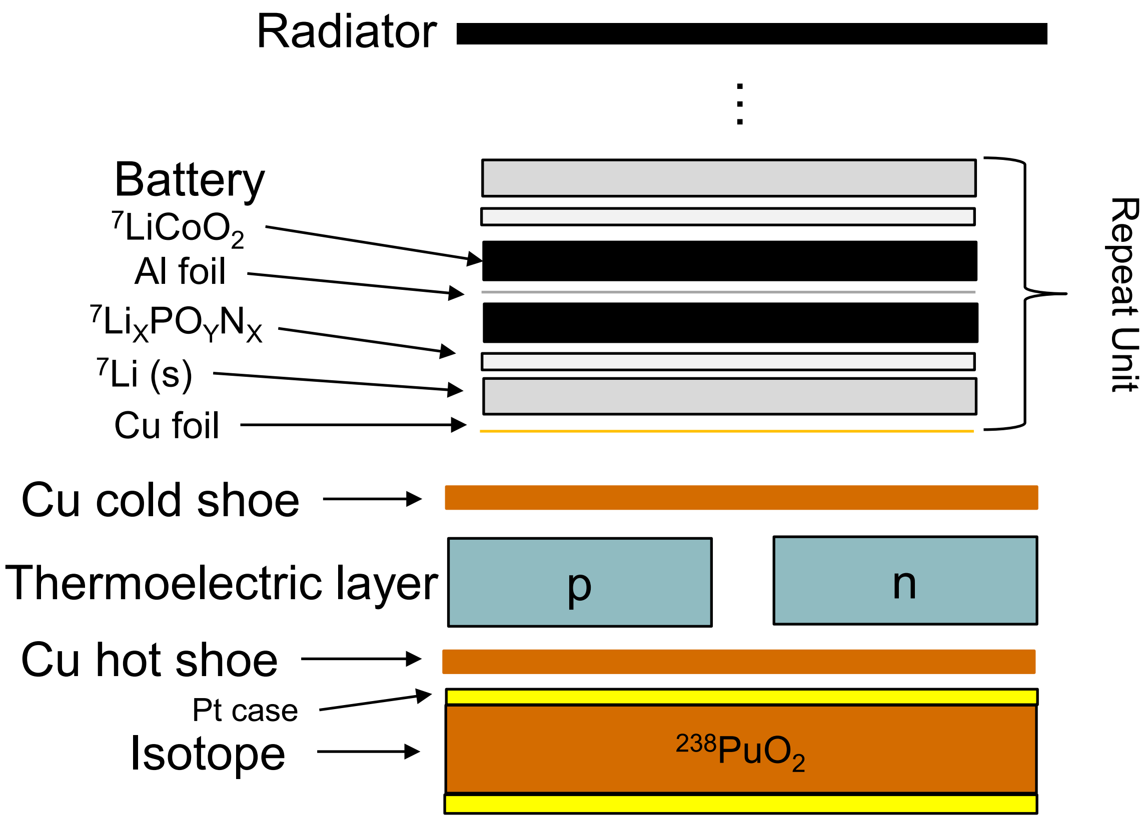
***Modular power tiles for missions***

# APPLE Stack Design

APPLE Power Core



Full Stack

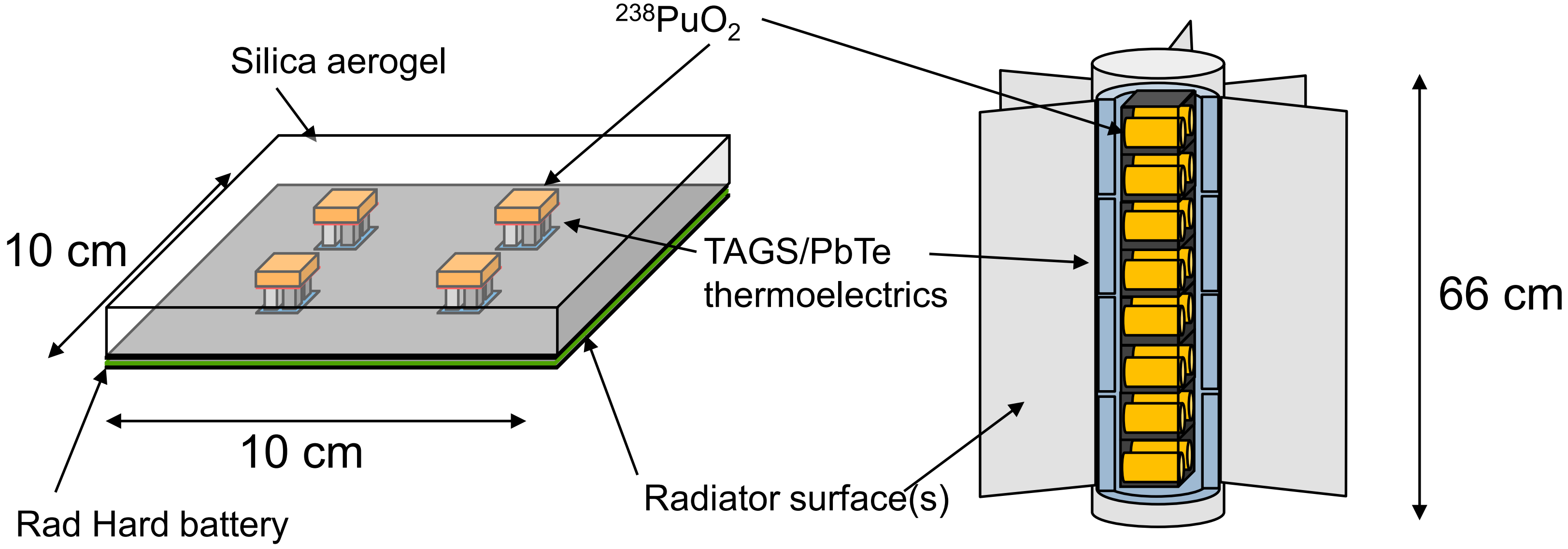


Each tile has 4 Power Cores distributed for an even thermal profile.

The radiation hard battery uses $^7Li$ to avoid capture of secondary neutrons for radiation effects.

***The modularity of the design allows for as many units as needed for any size mission***

# *Comparing MMRTG design to APPLE*



| APPLE | MMRTG |
|---|---|
| Mass: 0.075 kg | Mass: 45 kg |
| BOL power: 1.2 W | BOL power: 125 W |
| Power Density: 16 W/kg | Power Density: 2.8 W/kg |
| Efficiency: 8.6% | Efficiency: 6.2% |
| $^{238}$Pu: 0.024 kg | $^{238}$Pu: 11.52 kg |
| Battery: 5 Wh | Battery: NA |

APPLE is more efficient due to a larger effective radiator area. In addition, next generation designs can use higher efficiency thermoelectrics due to a lower operating temperature.

***APPLE reduces Pu needs through higher efficiency and waste heat utilization***

# Thermal Sims

- Thermoelectric energy conversion is dependent on the difference between the hot and cold shoes. A larger radiator can lower the $T_{cold}$ for a higher efficiency.

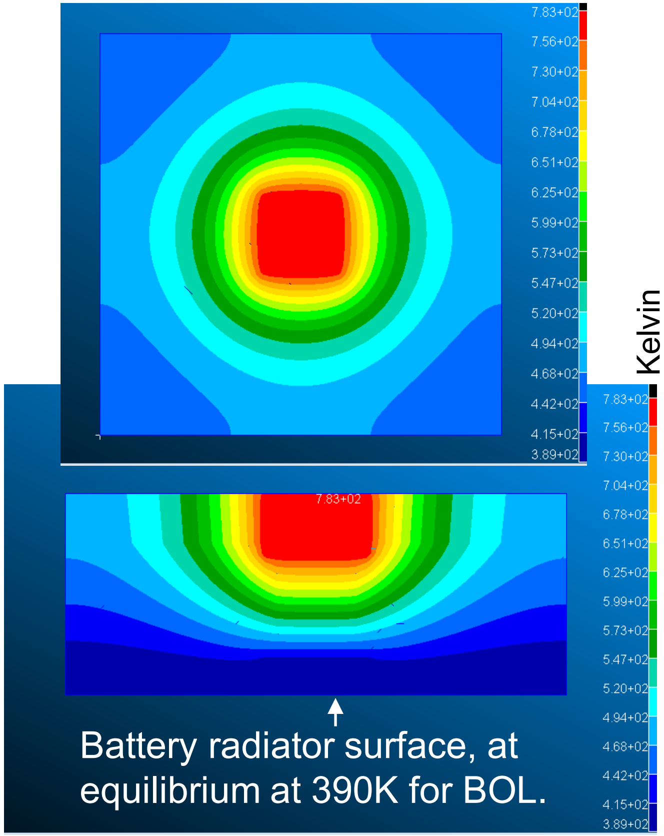
$$ZT = \frac{S^2 T}{\rho\lambda}$$

$$\eta_{max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_{cold}}{T_{hot}}}$$

- Thermal simulations showed that locating the battery at the thermoelectric cold shoe/radiator junction maintains a temperature range between 60℃ and 140℃ for the battery while the hot shoe thermoelectric junction remains at 527℃. This requires high temperature solid state batteries.

- Simulations of an RTG design for NASA missions show that a battery radiator can function to regulate RTG and thermoelectric temperature while maintaining a battery functional temperature over life.

Thermal sim of radioisotope core with a battery radiator surface



Battery radiator surface, at equilibrium at 390K for BOL.

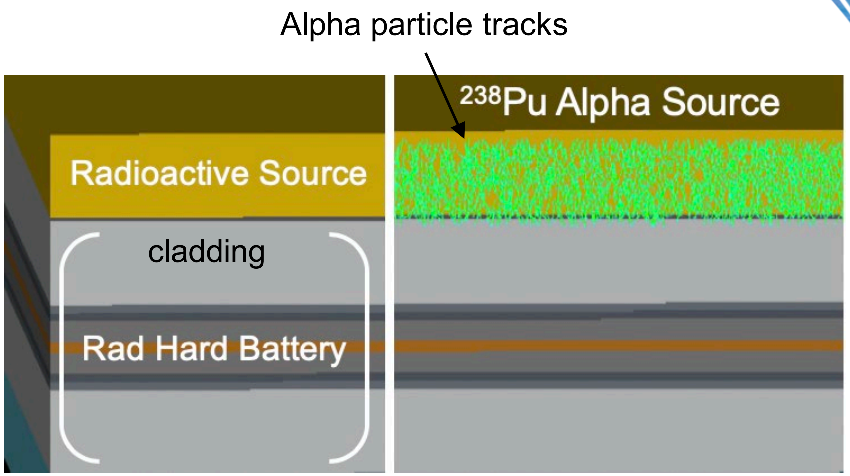
- The APPLE design has a thermoelectric conversion efficiency 37% better than the NASA MMRTG, using the same isotope and thermoelectrics, primarily due to the larger radiator (25:1 vs 5:1).
  - This larger radiator displaced the battery mass for the vehicle.

***We can tailor ΔT, temperatures, and thicknesses of materials***

# Radiation Simulations

- Radiation simulations of the alpha source $^{238}PuO_2$ showed no significant penetration of the alpha particles outside of the $PuO_2$ or material cladding, due to the high interaction cross section of the alpha particles.
  - Modelling of the radiation dose and capture depth indicates that $^{238}PuO_2$ is the optimal heat source for APPLE, with no need for radiation shielding for the battery. Other isotopes considered: $^{90}$Sr and $^{241}$Am.
  - It is unlikely that $^{238}$Pu radiation will be a significant factor in the exposure of the battery.

- For galactic cosmic radiation (GCR) and solar flare particles large sections of the battery have little shielding from the spacecraft; only the aerogel insulation and the carbon radiators.



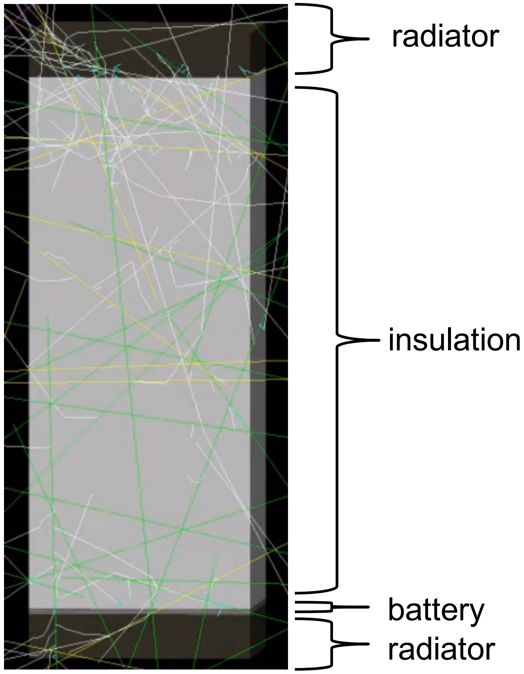
Simulation of rad hard battery placed on the isotope cladding

Simulation of rad hard battery between the radiator and the aerogel insulation.

Green = Li

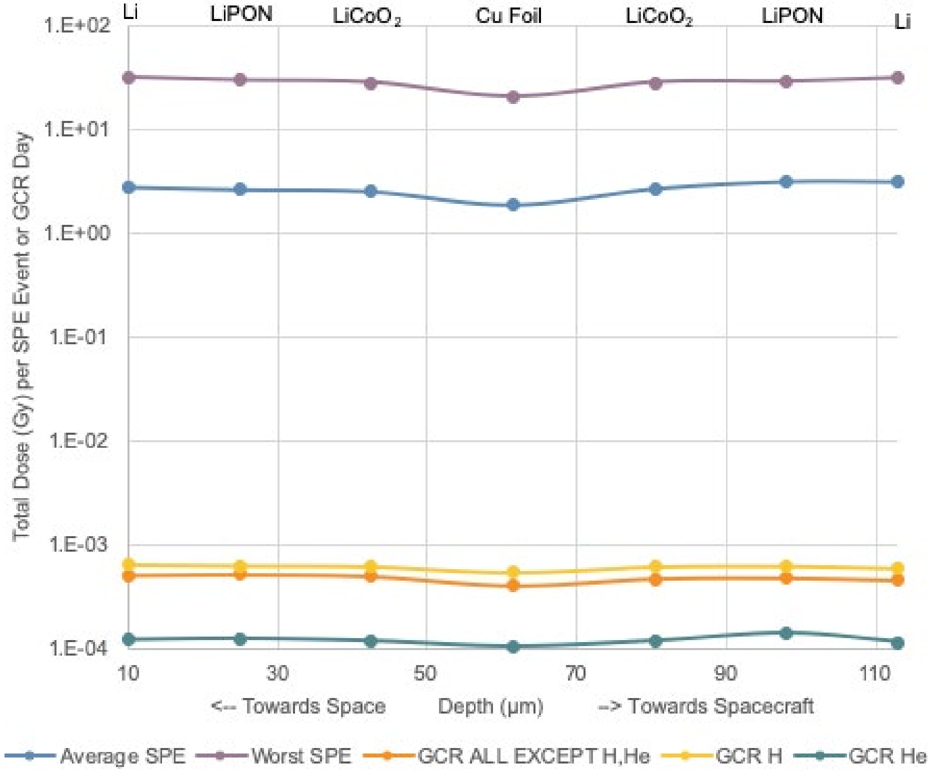
Yellow = heavier particles

White = secondary particles generated

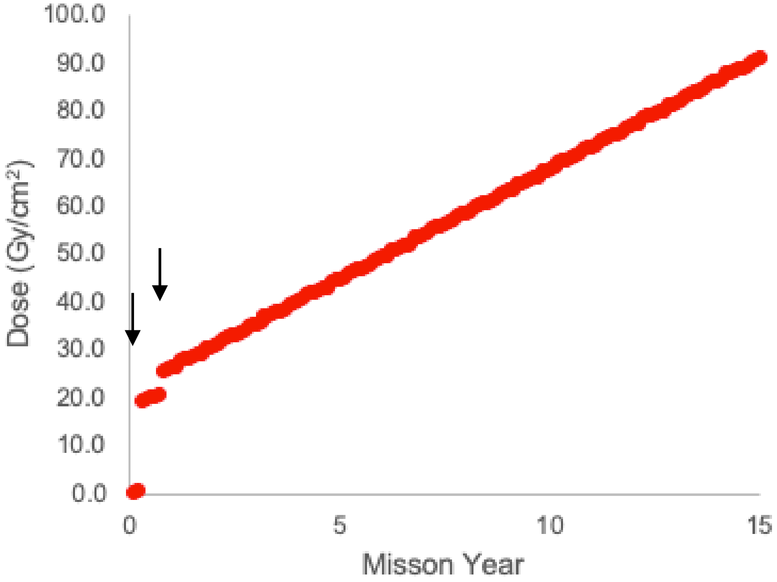


***The battery must survive interplanetary radiation environment***

# *Radiation Dose*



Dose per layer of battery from both galactic cosmic radiation sources, as well as from solar flare (SPE) exposures show uniform deposition in the battery.



Total accumulated dose (Gy) for a mission to Jupiter launching around solar minimum. Significant amount of dose from solar flares (average) in local space.

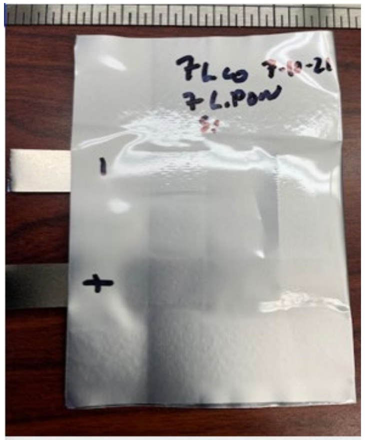
Mission dose of radiation is highly dependent on time spent in the inner solar system and solar activity. By the time the vehicle reaches Jupiter and beyond, dose accumulation is primarily from GCR.

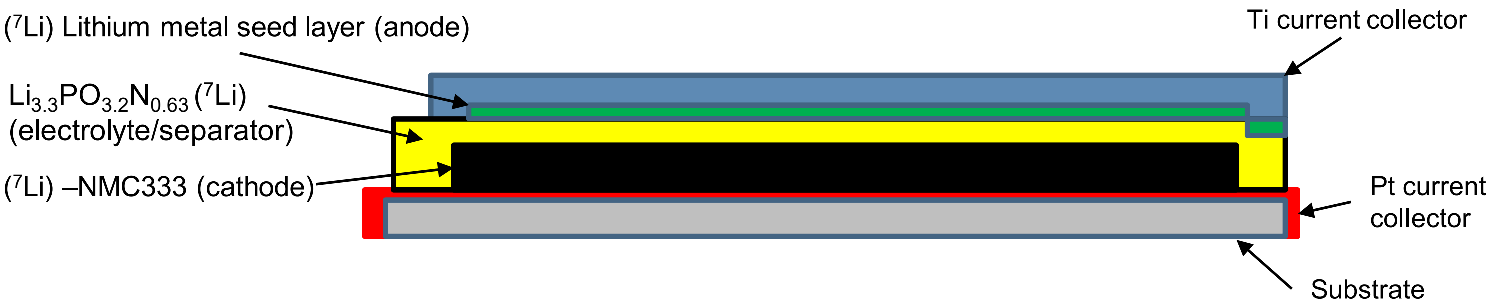
***Planned destinations have small contributions from solar flares***

# *Radiation Hard Battery Design*

All solid state cells fabricated at ORNL, utilizing neutron transparent $^7$Li. Without fragile polymer separators and organic electrolytes, the cells should withstand the radiation exposure from cosmic rays and solar flares.

Cell under radiation testing




($^7$Li) Lithium metal seed layer (anode)

$Li_{3.3}PO_{3.2}N_{0.63}$ ($^7$Li) (electrolyte/separator)

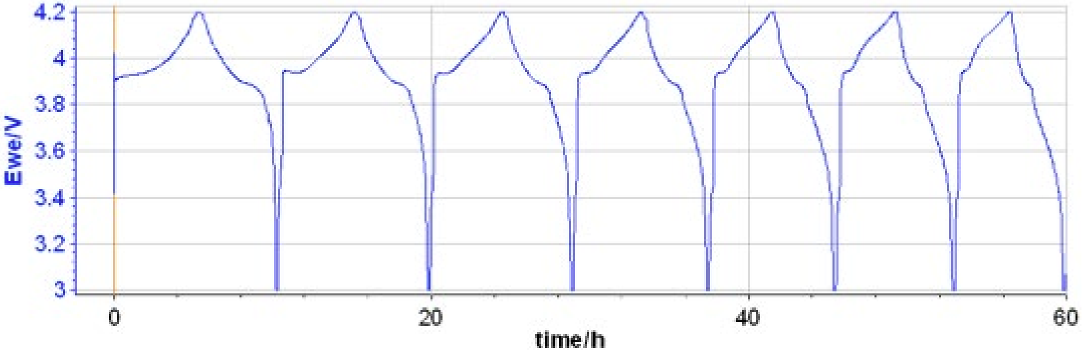
($^7$Li) –NMC333 (cathode)

Ti current collector

Pt current collector

Substrate

Cells went through characterization for baseline evaluation. Cell cycling properties will be compared before and after radiation exposure, as well as comparison to unexposed cells.



Representative cycling data for cell (C/5)

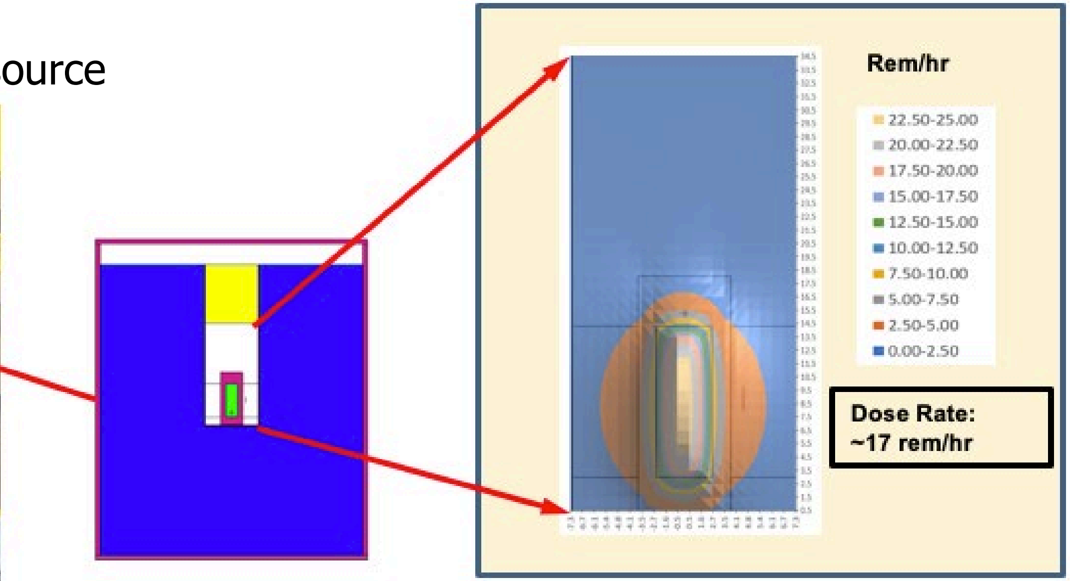
***Solid state batteries are robust and have a wide operating temperature***

# Radiation Testing

- Cells are being tested at ORNL using a radiation testing setup.
- Radiation source Am-Be-3215:
  - *Neutrons:* $S_n = 6.81\mathrm{E}{+}06$ *n/s*
  - *Associated Am/Be Gamma; E = 4.438 MeV*

- First test is running for 1 month, for ~ 12,000rem. This is approximately equal to the first 3 years of an Earth to Jupiter mission.

Am-Be Radiation source



Calculation of radiation exposure

***Radiation testing is ongoing***

# Status and Next Steps

- We have designed a 75g, 1.2$W_e$, 50 Wh APPLE tile.
  - The small size allows for missions of a range of size to be developed, using as many APPLE tiles as needed.

- Thermal sims show significant improvements in thermal conversion efficiency are possible due to larger radiator surface area.
  - Radiator heat transport can be to space, or can be to spacecraft to reduce heating needs.

- The thin form factor results in significant radiation exposure to the battery over long mission life, and the battery needs to be radiation hard.

Next Steps

- Evaluation of battery performance post radiation.  Testing of cell performance relative to initial capability and cell life.

- Replacing TAGS/PbTe thermoelectrics with more efficient skutterudite thermoelectrics.

- Demonstration of full stack (heat source/thermoelectrics/battery/radiator) performance *in vacuo*.