Solar Energy in Our Universe – Latest Solar Systems Technology for Planet Earth & Solar System Exploration – Expanding Our Energy "Toolbox"

presented at

2016 IDTechEx Show! Santa Clara

Energy Harvesting Session

Santa Clara, CA

Dr. Terry J. Hendricks, P.E., ASME Fellow[1]

[1] Technical Group Supervisor, Thermal Energy Conversions Applications & Systems Group

Jet Propulsion Laboratory, California Institute of Technology

Pasadena, California, USA

17 November 2016

Copyright 2016 California Institute of Technology. U.S. Government sponsorship acknowledged.

AGENDA

- Recent Spacecraft Solar Power Systems
- Terrestrial Solar Energy Recovery Technologies
  - Full Spectrum Solar Energy Utilization (Waste Heat Here)
  - Spectrum Splitting Systems
  - Thermal Energy Storage
- Final Thoughts

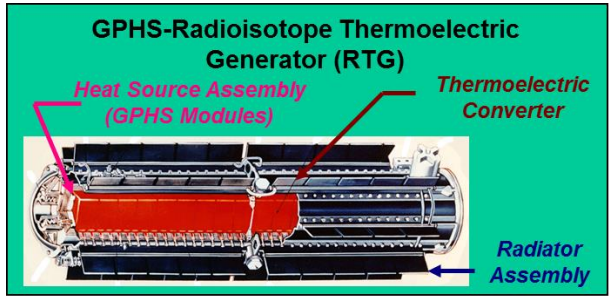
NASA Science Exploration Missions Need for Both Solar & Radioisotope Power Systems (RPS)

Solar power systems serve a *critical role* in the scientific exploration of the near-Earth solar system

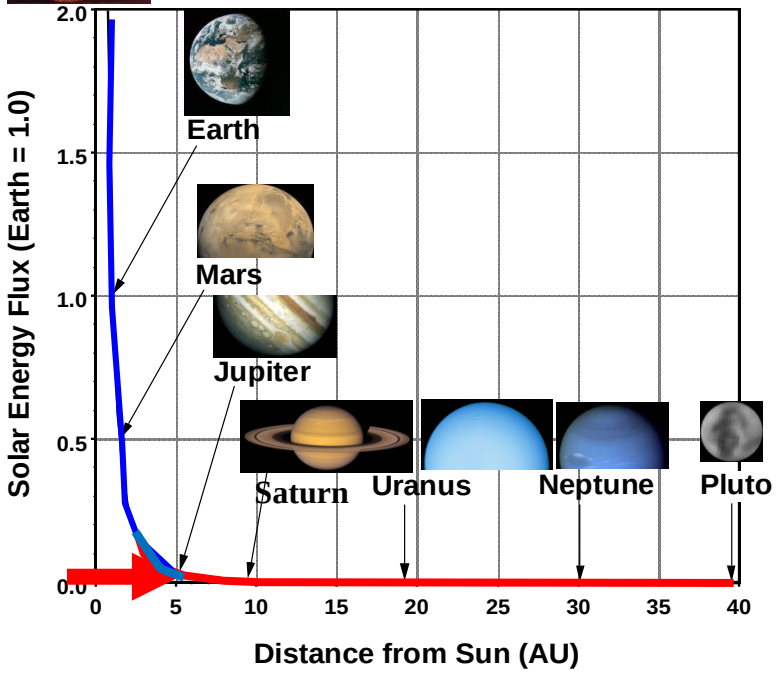
- Moderate power levels up to 100 kW
- Operations dependent on distance and orientation with respect to Sun

Radioisotope power systems (RPS) serve a *critical role* in the scientific exploration of the deep-space solar system

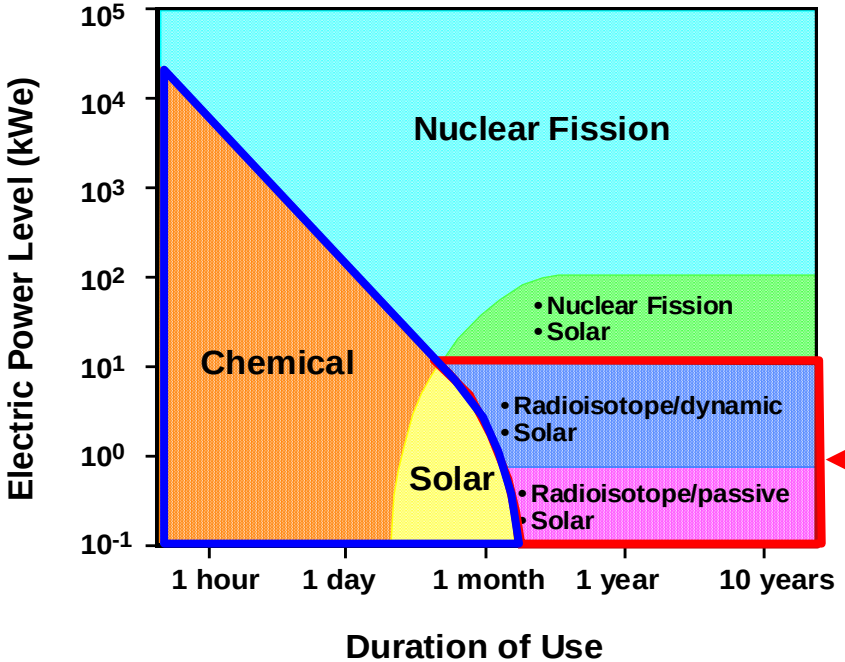
- Low to moderate power levels (~100 W - 1 kW) for more than several months
- Operations independent of distance and orientation with respect to Sun

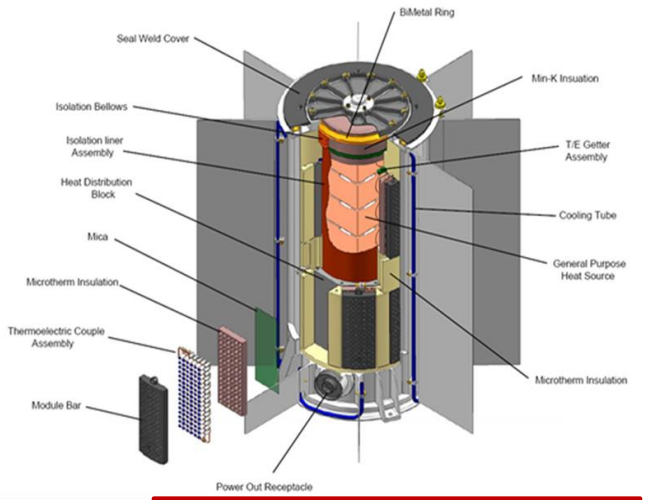


Inherent limitation of solar power



Best candidates for maximizing specific power





Multi-Mission RTG

Used on Mars Curiosity Rover

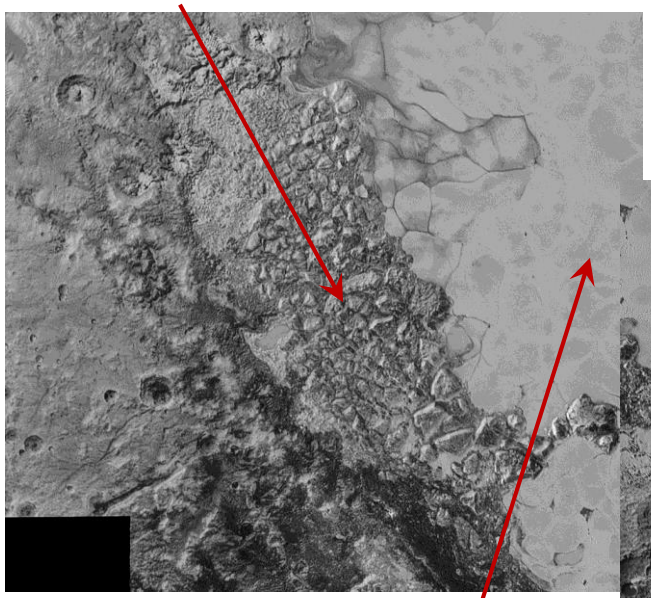
New Horizons to Pluto (2006)

Heart of Pluto

With Love,
Pluto

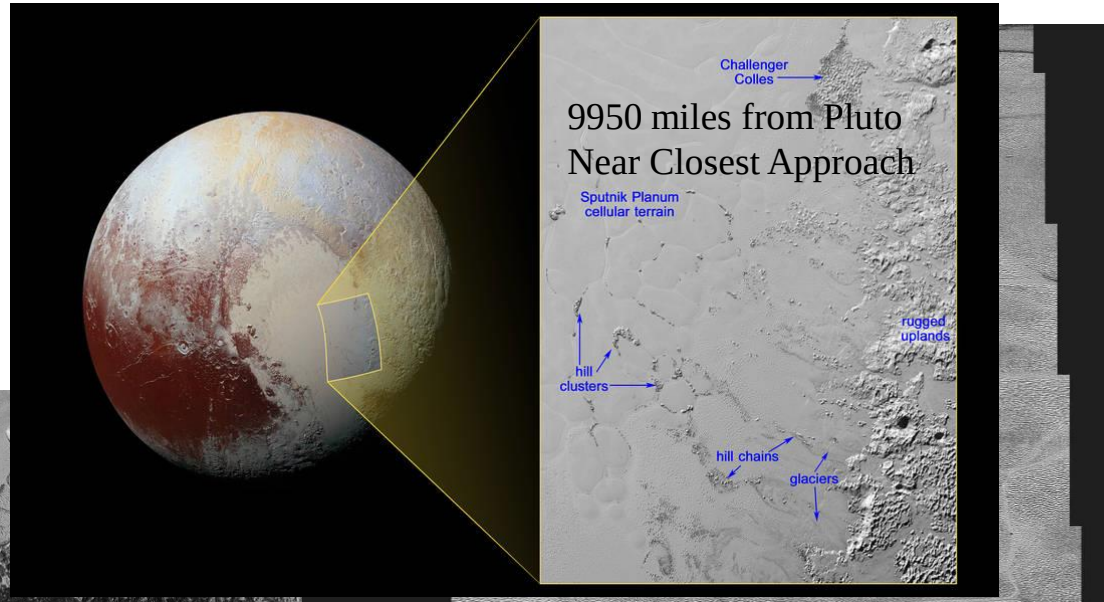
476,000 miles from Pluto

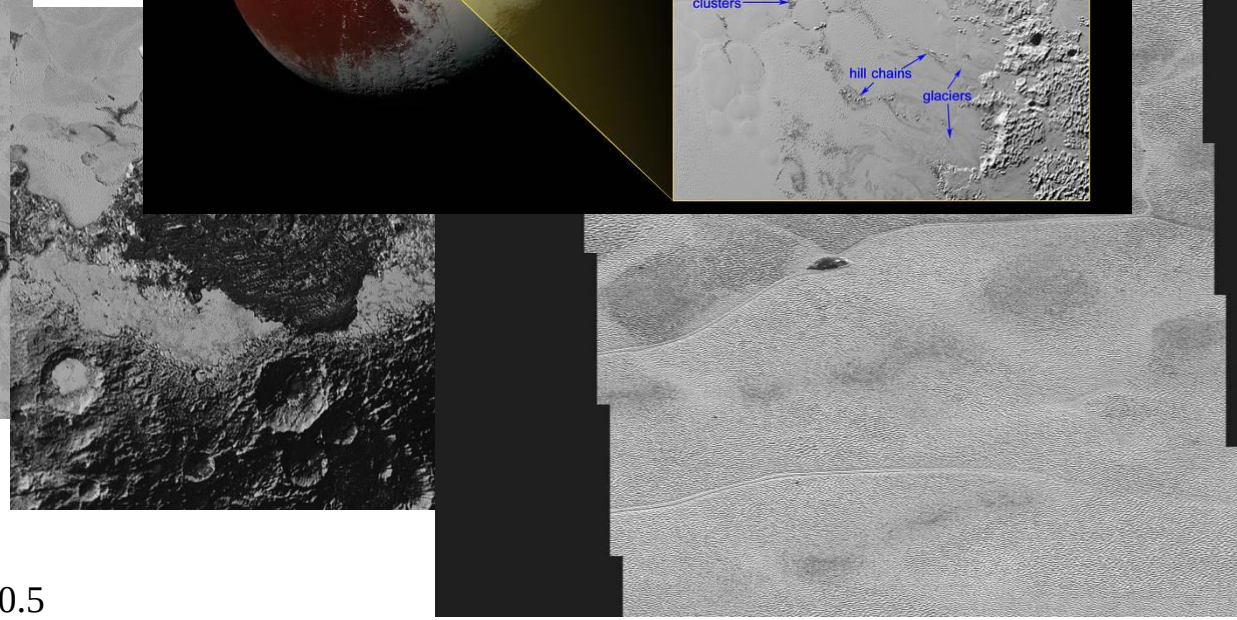
Large region of jumbled,
broken terrain



Vast, Icy Plain – Sputnik Planum
50,000 miles from Pluto

300 mile wide image, smallest features 0.5 mile wide





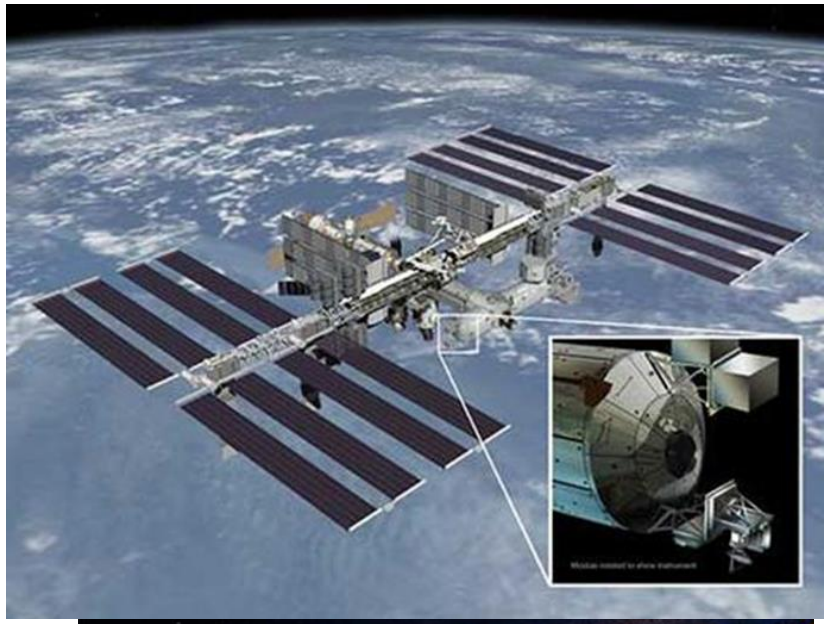
10,000 miles from Pluto

RTG Power Made this All Possible
SiGe TE Materials

Water ice hills are floating in a sea of frozen Nitrogen

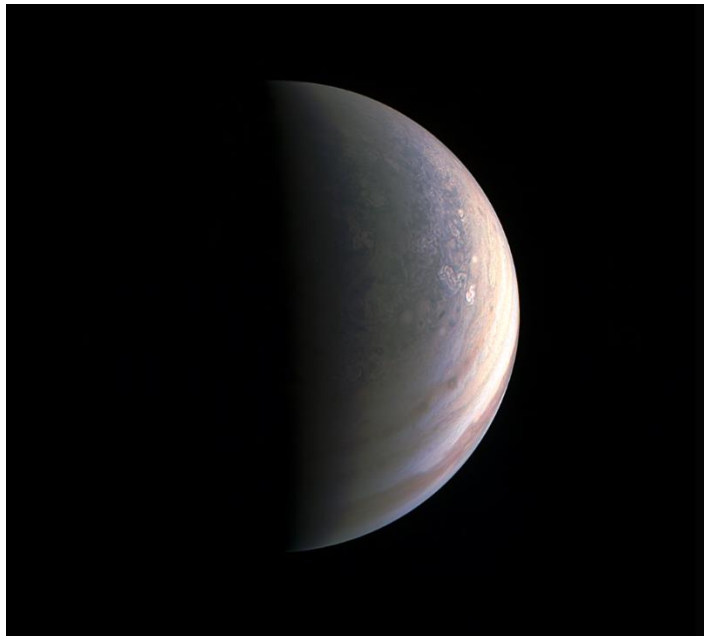
SPACECRAFT SOLAR SYSTEMS
INTERNATIONAL SPACE STATION & DAWN & JUNO

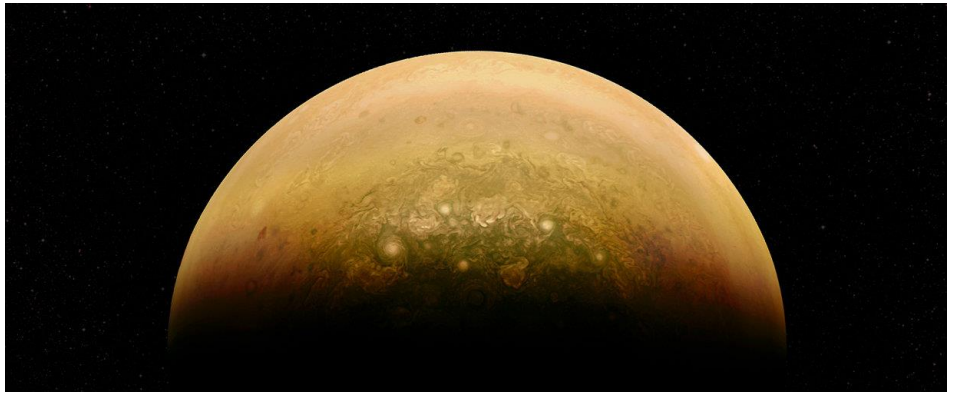
- Solar Photovoltaic Power System Used to Power Current International Space Station
  - Silicon
  - Eight 375 m^2 Solar Arrays, 84 – 120 kW
- Dawn Spacecraft
  - Asteroid Chasing - Vesta and Ceres Asteroids
  - Hyper-efficient Ion-Propulsion (Xenon fueled)
  - 10 kW of Solar Power @ 1 A.U.; 1.3 kW @ 3 A.U.
  - InGaP/InGaAs/Ge Triple Junction PV Cells (35.4 m^2)
  - Low Intensity, Low Temperature PV Effects Considered (Emerging)
- Juno Spacecraft
  - Launched to Jupiter in July 2011; Arrived July 2016
  - InGaP/InGaAs/Ge Triple Junction PV Cells
  - 256 sq. ft. (23.8 m^2) per array, 3 arrays
  - Study Jupiter Atmosphere, Magnetic, & Gravity Fields
  - H_2O and NH_3 Measurements in Atmosphere



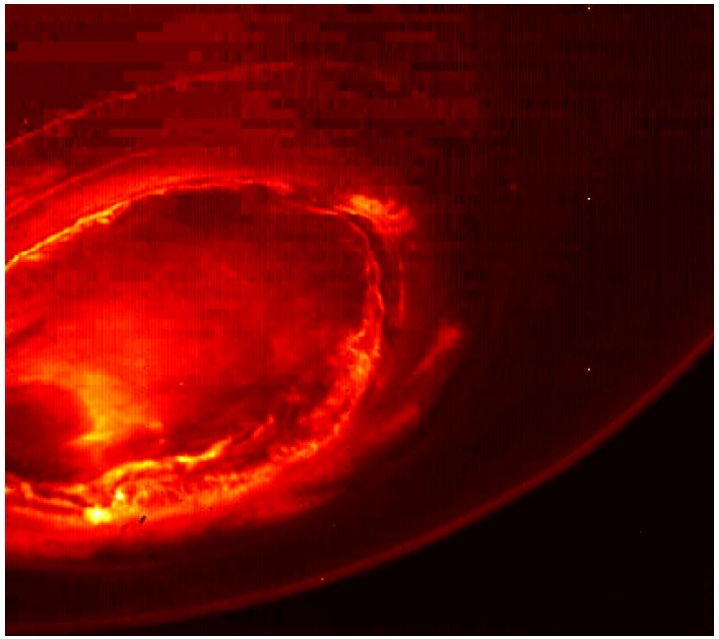
Latest From Juno @ Jupiter

- North Pole of Jupiter – 2500 miles Above Clouds
- Notice Absence of Banded Cloud Structure





- Deep in Jupiter's atmosphere, under great pressure, H_2 gas is squeezed into fluid known as metallic hydrogen
- At these enormous pressures, the H_2 acts like an electrically conducting metal
- Believed to be the source of the planet's intense magnetic field
- Powerful magnetic environment creates the brightest auroras in our solar system, as charged particles precipitate down into the planet's atmosphere.
- Juno will directly sample the charged particles and magnetic fields near Jupiter's poles for the first time

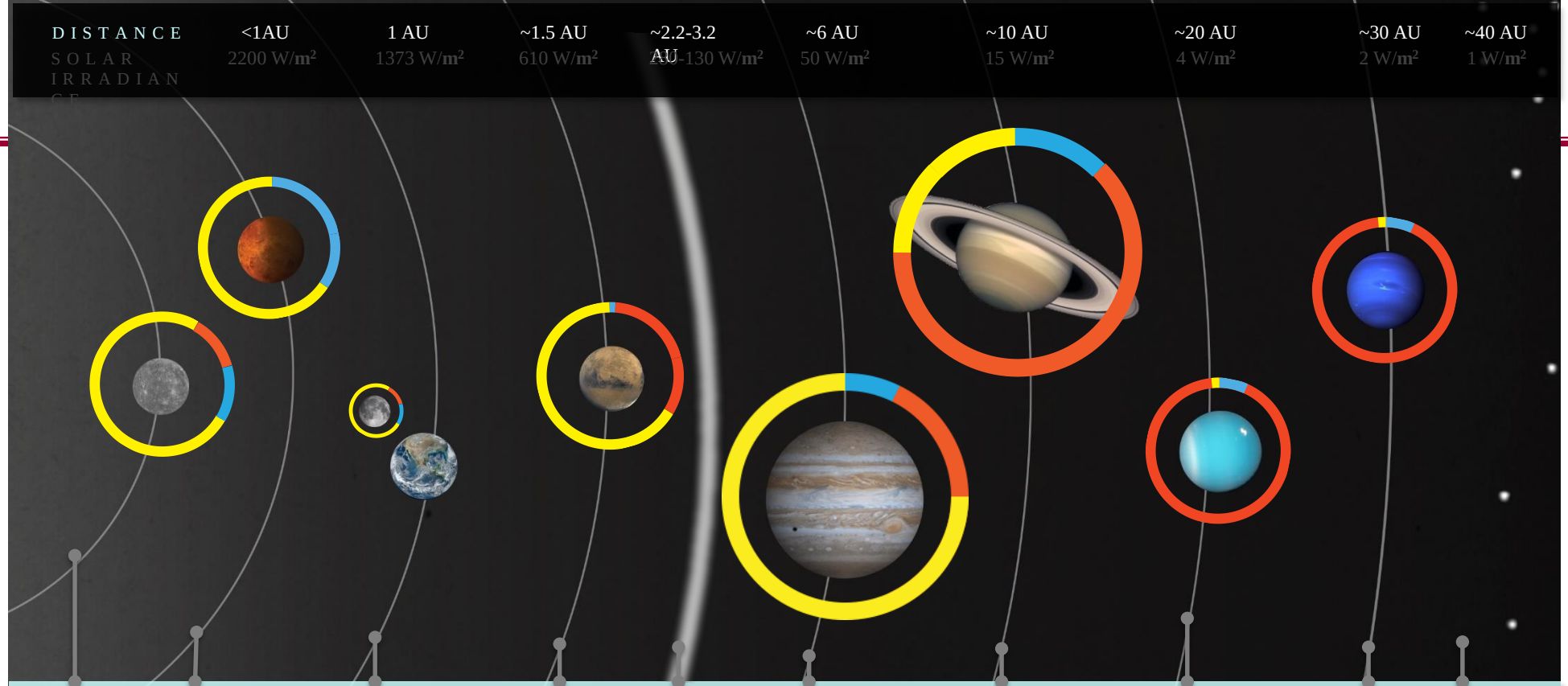


Southern Aurora 2500 miles above clouds

Latest From Juno @ Jupiter

- Jupiter pictures during the Juno orbit as it swings in and swings out in elliptical orbit
- This is its first arrival and departure in e-orbit
- More information at:

http://www.jpl.nasa.gov/news/press_kits/juno/science/



MERCURY

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS

SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS

SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER

SOLAR
- Orbiters
- Flybys

RPS
- High capability orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN

SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys

BATTERIES
- Atmospheric probes

NEPTUNE

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015[1]

(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015

Solar
RPS
Primary Battery

Approximate relative applicability of power technologies to target body missions

Imagine, Innovate, “Instigate” to Real-World Applications

[1]

39,000 m Up at Edge of Space
Mach 1.25

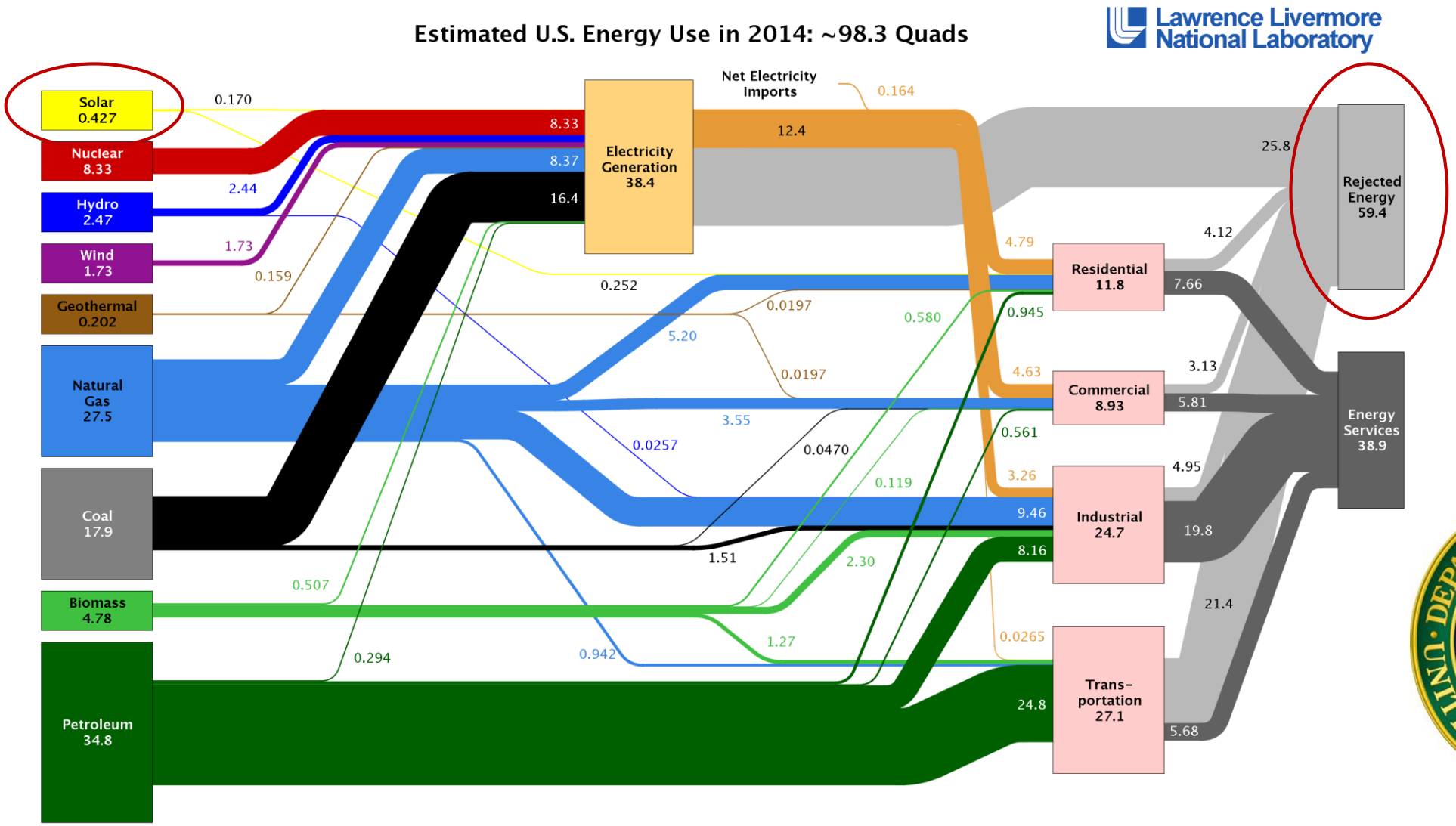
Looks Like Space to Me!!

[1]

So Talking About Dual-Use Technologies …..

[1] http://en.wikipedia.org/wiki/Felix_Baumgartner
http://www.youtube.com/watch?v=FHtvDA0W34I

United States Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% [illegible] industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Waste Heat To Be "Harvested"

  59.4 Quads

- Up ~ 5Quads From 2009

Full-Spectrum Hybrid Solar / Thermal Cycle Power Systems

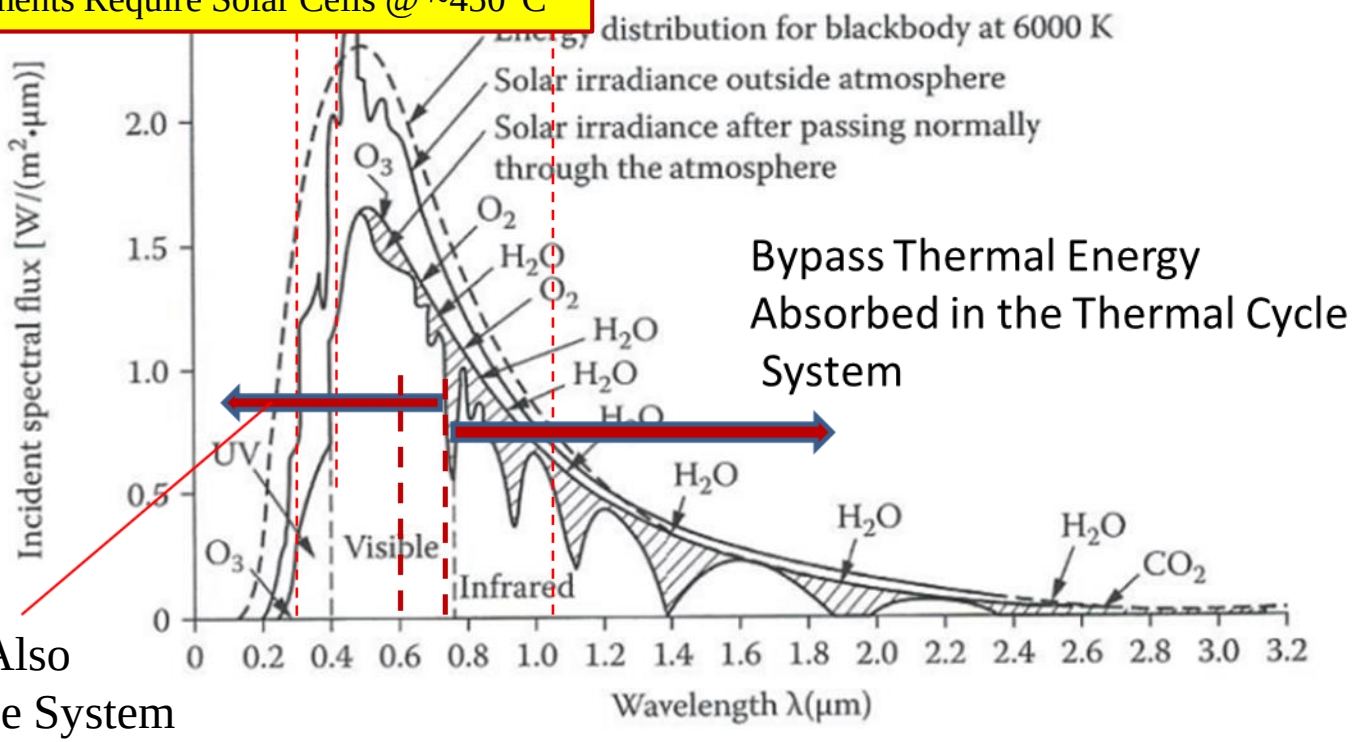
- Terrestrial Concentrated Solar Systems
- Hybrid Concentrated Solar PV/Thermodynamic Cycle Wavelength-Splitting Systems to Achieve High Exergy Efficiency
- Optimum λ-split @ ~1.7 eV – 1.11 eV (0.73 μm -1.12 μm)

Thermal Technologies

Solar Cells

- Energy Recovery Opportunity
  - Solar PV Cells Do Not Capture Everything
  - Higher Wavelengths Have Significant Energy Content
  - NASA Overlap: Venus Environments Require Solar Cells @ ~450°C

- **Technical Challe**
  - High Temperat
  - Compact Stirling cycles, Brayton cycles, Organic Rankine cycles
  - Wavelength splitting (efficiency)
  - Thermal interfaces
  - High-Temperature thermal energy storage (<$15/kW$_{th}$)
  - Cost
    - LCOE ~ $0.06/kWhr is high bar

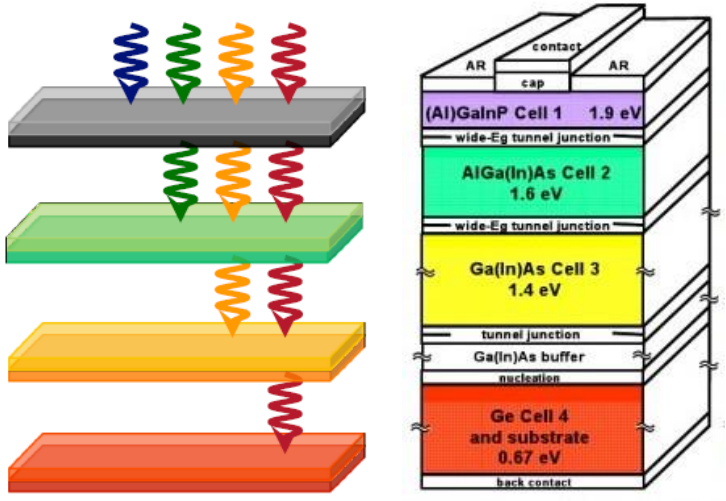


Bypass Thermal Energy Absorbed in the Thermal Cycle System

Cell Thermalized Energy Also Absorbed in Thermal Cycle System

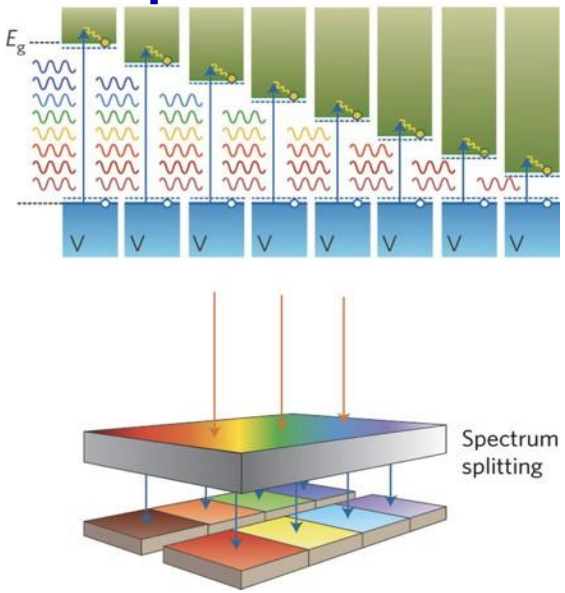
Multijunction Architectures

Monolithic Series Connect



- Lattice match or slight lattice mismatch -> constrains choice of subcell bandgaps
- Current matching reduces energy yield
- Fewer subcells (2-4)

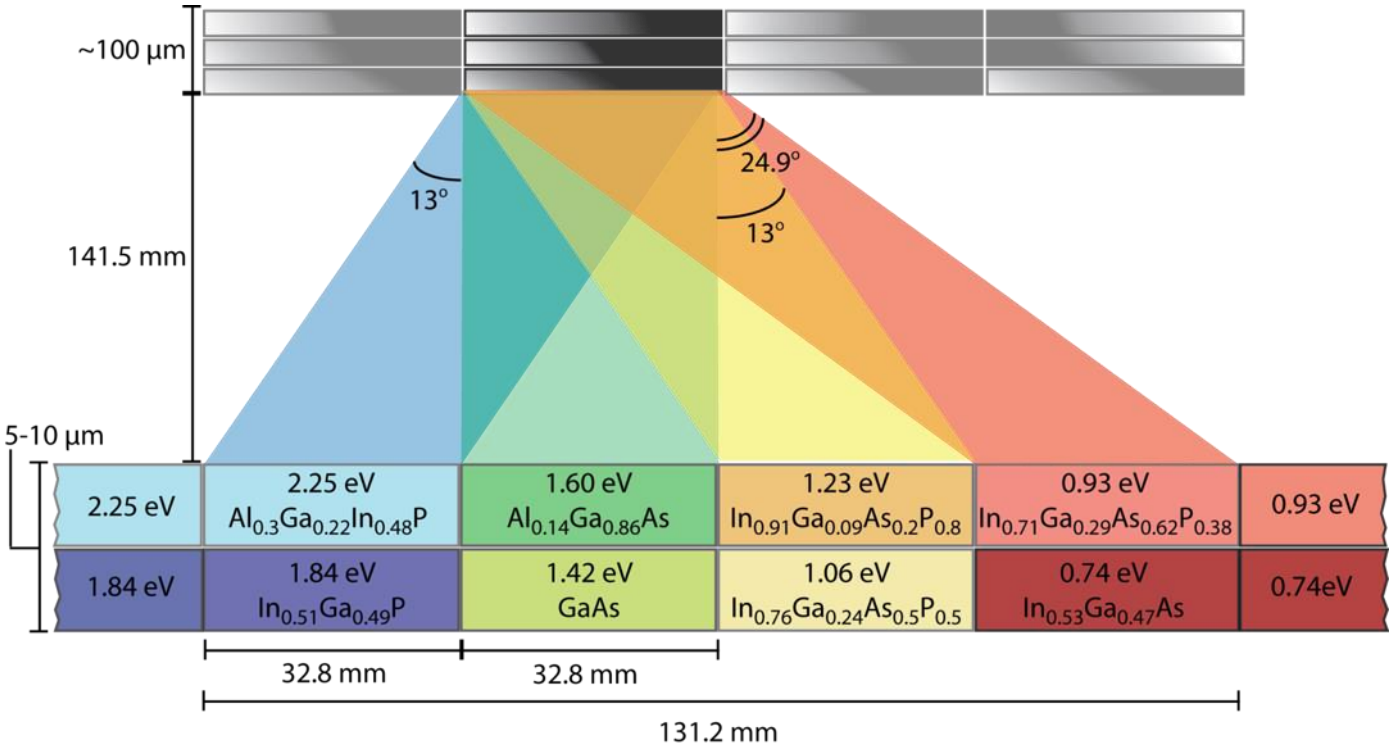
Spectrum Splitting Independent Connect



- More subcells (6-15)
- Almost optimal bandgaps
- Independent electrical connections
- More complex assembly
- Spectral splitting optics required

Caltech

Four-way Holographic Spectrum Splitting



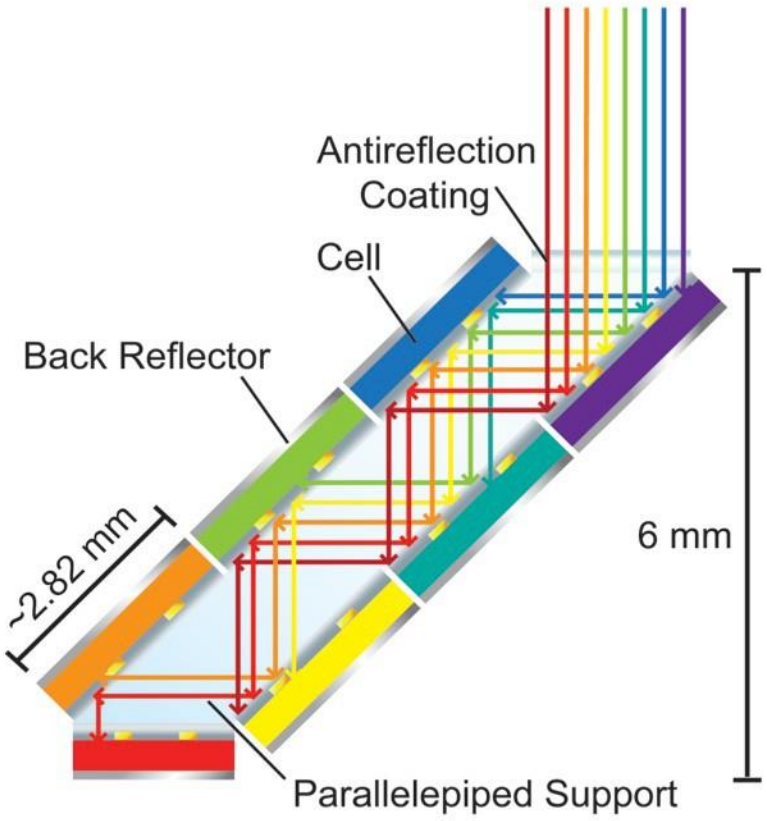
- 8 lattice-matched subcells
- Materials grown on GaAs and InP

- Commercially available gratings
- 3 x 4 gratings: tractable design problem

Escarra, et. al,, PVSC (2013)

Caltech

Polyhedral Specular Reflector



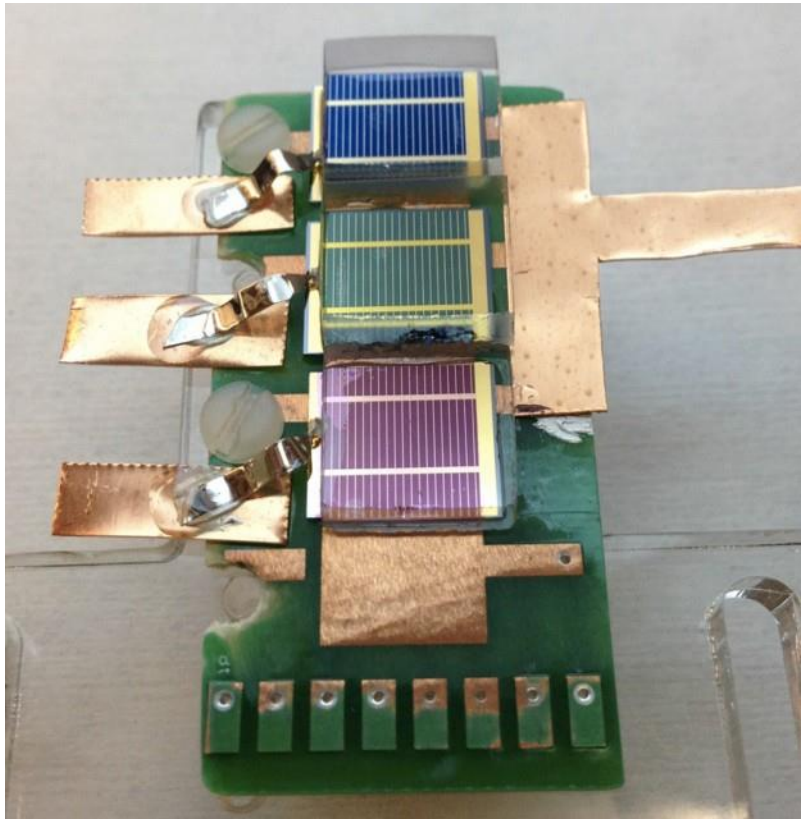
E_g (eV)	III--V Alloy	Substrate
2.15	$Al_{0.20}Ga_{0.32}In_{0.48}P$	GaAs
1.84	$Ga_{0.51}In_{0.49}P$	GaAs
1.58	$Al_{0.1}Ga_{0.9}As$	GaAs
1.42	GaAs	GaAs
1.15	$In_{0.87}Ga_{0.13}As_{0.28}P_{0.72}$	InP
0.94	$In_{0.71}Ga_{0.29}As_{0.62}P_{0.38}$	InP
0.74	$In_{0.53}Ga_{0.47}As$	InP

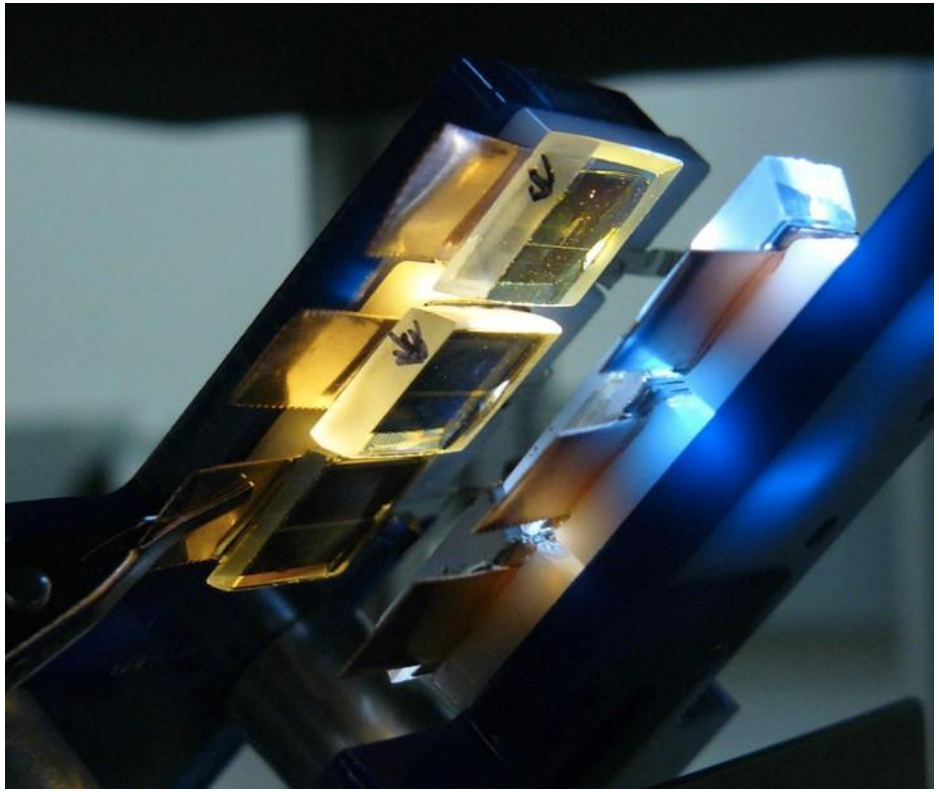
Cell modeling: average ERE of 0.3% and 90% of ideal J_{sc}

Eisler, et. al,, PVSC (2013)

Caltech

Polyhedral Specular Reflector Prototype





Proof of concept design incorporating 6 subcells

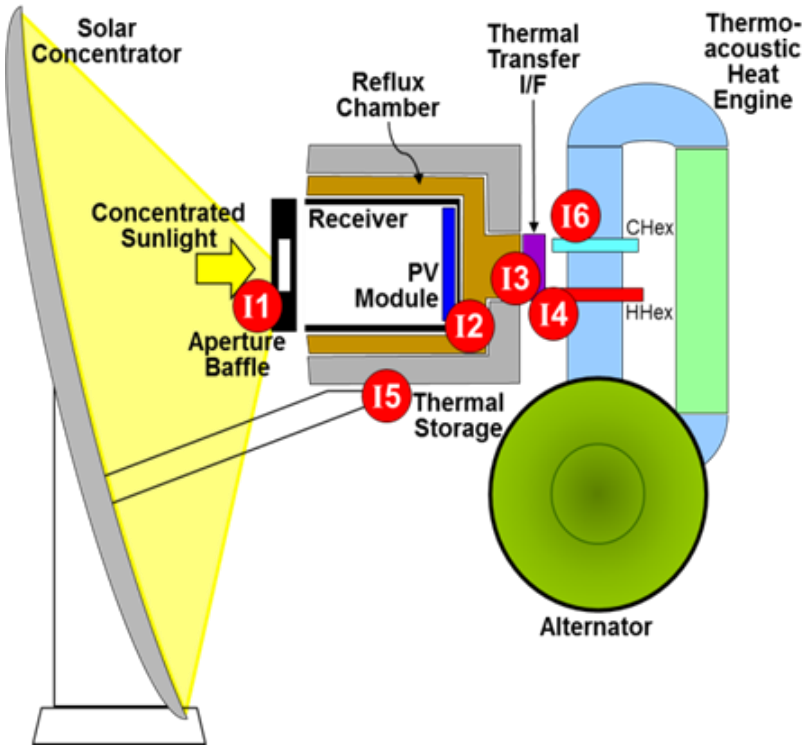
Projected Optical Efficiency = 80.4%

Caltech

Acknowledgment and Used with Permission From Professor Harry Atwater haa@caltech.edu

FSPOT-X System Description & Function

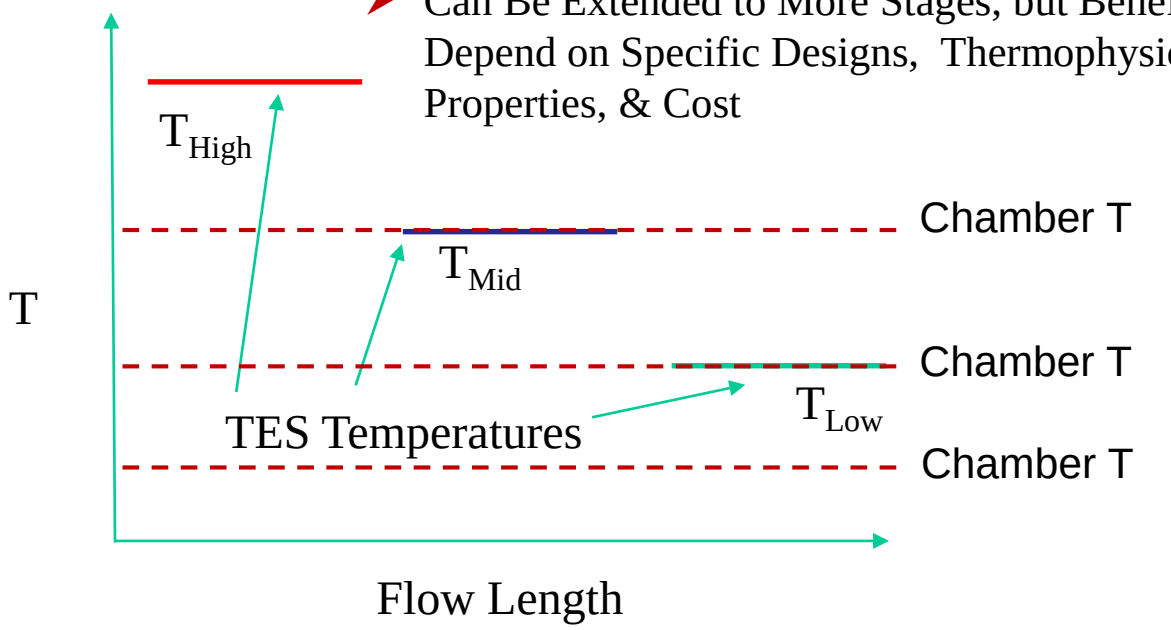
- Hybrid Photovoltaic (PV) / Thermoacoustic Power Conversion (TAPC) System Incorporating Thermal Energy Storage (TES)
  - Photovoltaics captures & converts energy @ low wavelengths
  - Reflux boiling system for efficient, low exergy heat transfer
  - TAPC Captures & Converts Thermal Energy @ Longer Wavelengths
  - TES Integrated into Reflux Boiling System To Store Thermal Energy
  - Effective high-temperature TES is required
- Benefits
  - Increased system-level performance (power & efficiency)
  - Increased system dispatchability – Longer off-sun operation
  - Leads to lower LCOE costs
- Goals
  - > 10 kWe TA engine at 300-350 C and 37 C reject temperature at > 25% TAPC efficiency
  - High-temperature PV efficiency >20% (@ 350°C)
  - Overall system efficiency ~44%
- Reflux Boiler / TES is Critical to System Operation
  - Low exergy thermal transport into TAPC
  - Low exergy thermal transport into/out of TES



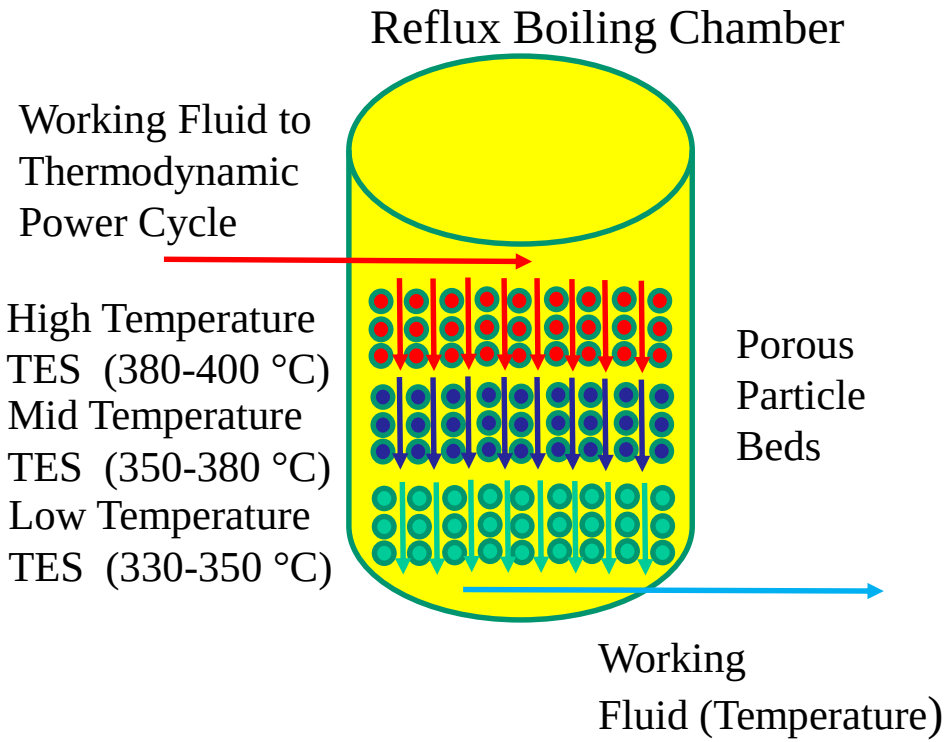
Multiple TES Materials

- Thermal Energy Storage (TES) Required to Reduced LCOE & Increase Dispatchability
- S_{Gen} ~ (Q/T) Can Be Lower in This Scheme – Lower Thermal Exergy
- Highest Temperature TES Gives Thermal "Switch" Capability

  - Allows One to Charge / Discharge in Incremental Steps
  - This Lowers the Total Thermal Exergy Loss in the Round-Trip Process
  - 90% Energy Storage in PCM with Higher Ultimate Storage Temperature
  - Can Be Extended to More Stages, but Benefits Depend on Specific Designs, Thermophysical Properties, & Cost

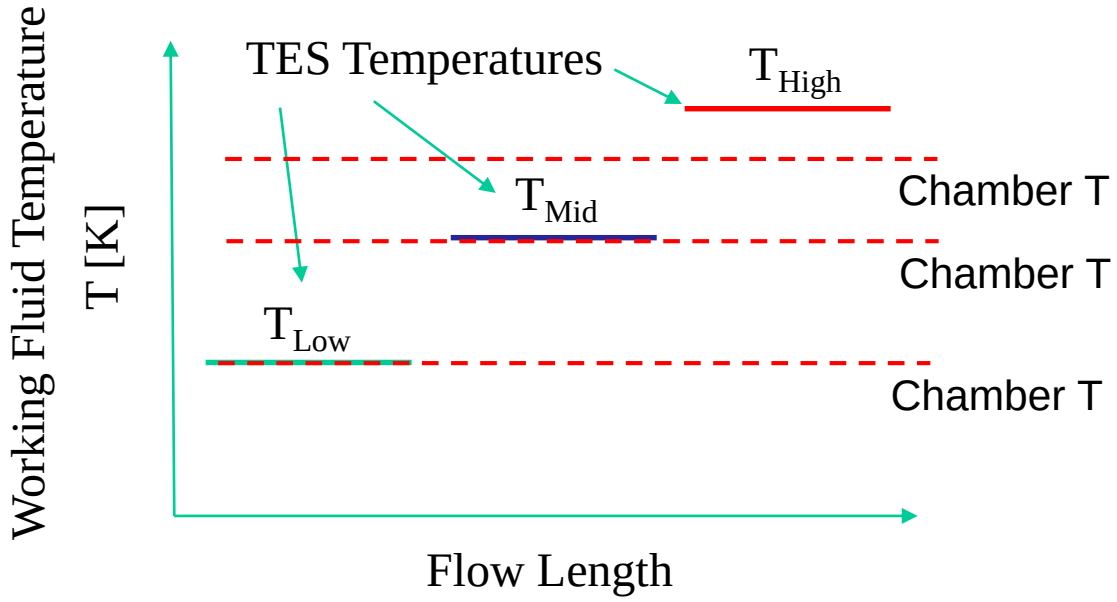


TES Charge Process

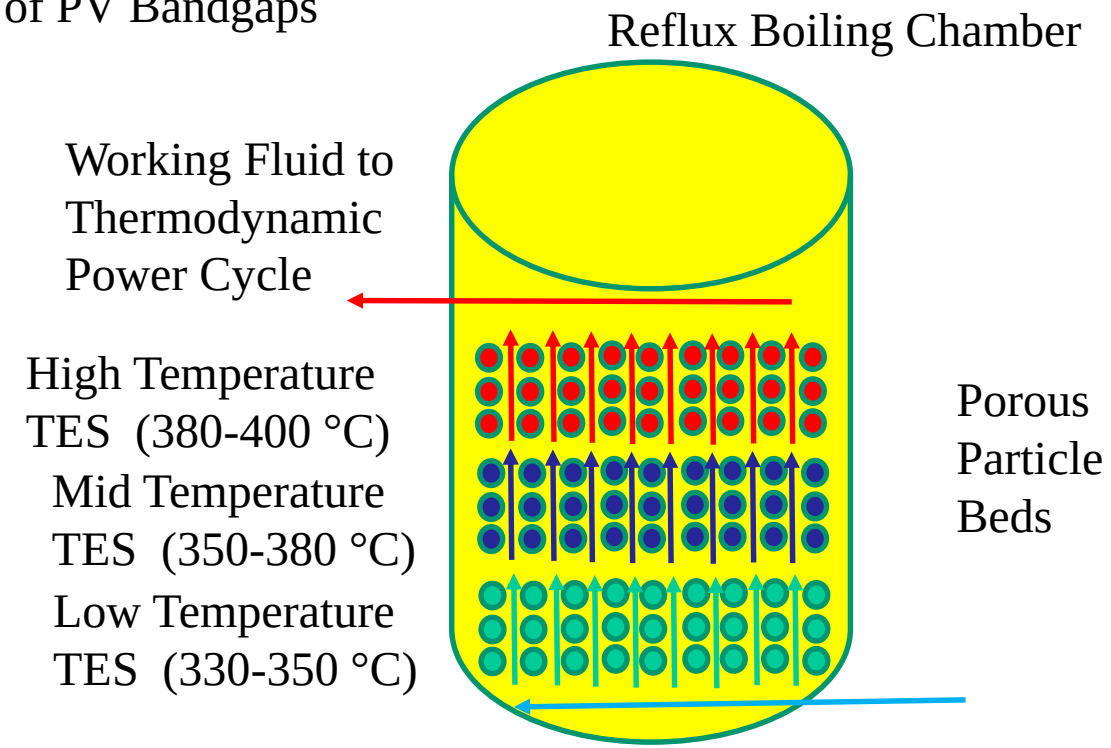


Multiple TES Materials

- $S_{Gen} \sim (Q/T)$ is Lower in This Scheme
- Highest Temperature TES Gives Thermal "Switch" Capability
- 3 TES Layer Analogous to 3 PV Bandgaps (Thermal Phonons vs. Near-IR/Visible Photons)
- Extending: Infinite TES Layer Analogous with Infinite Number of PV Bandgaps



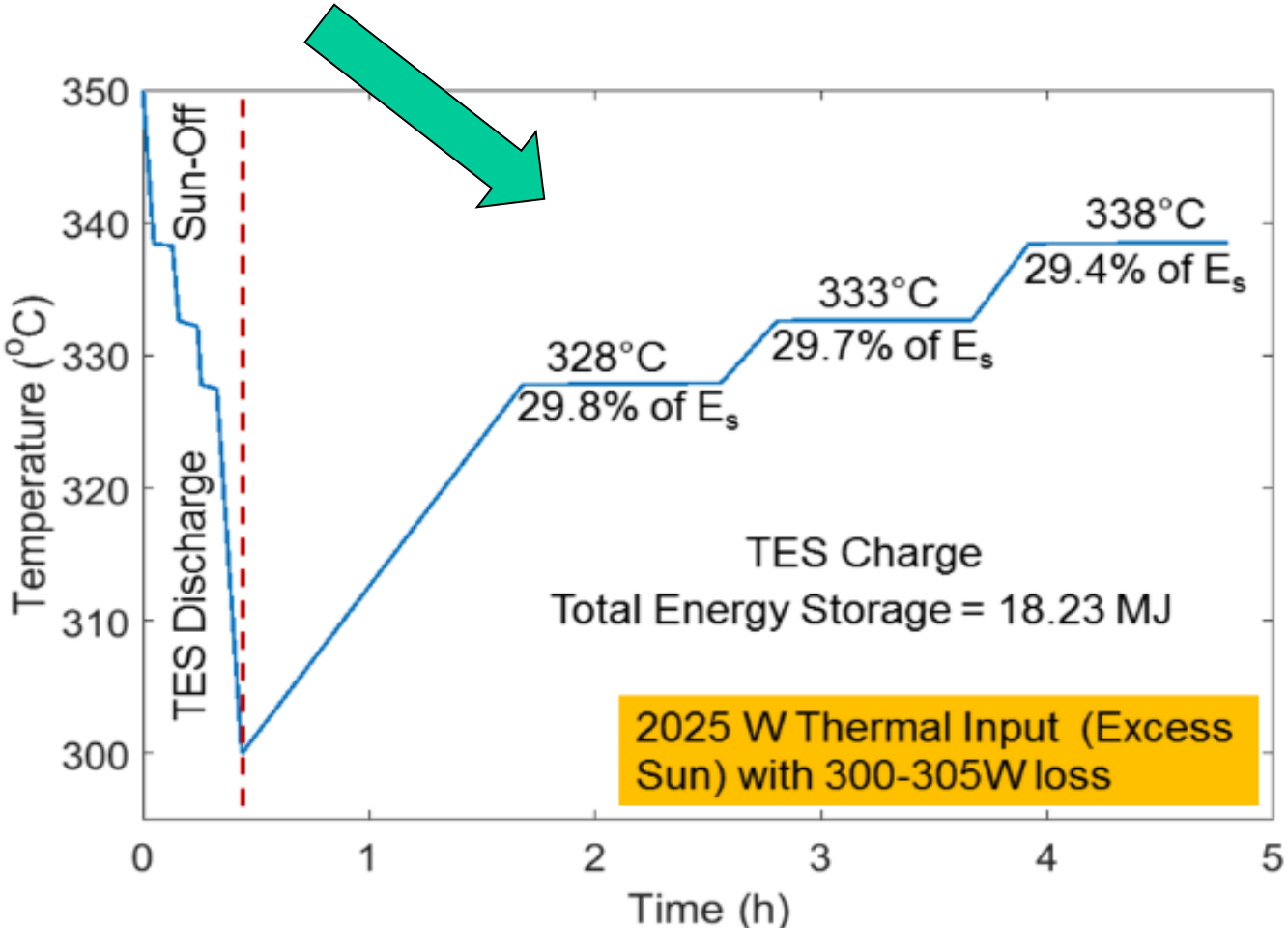
TES Discharge Process



Multiple Temperature-Staged Analysis

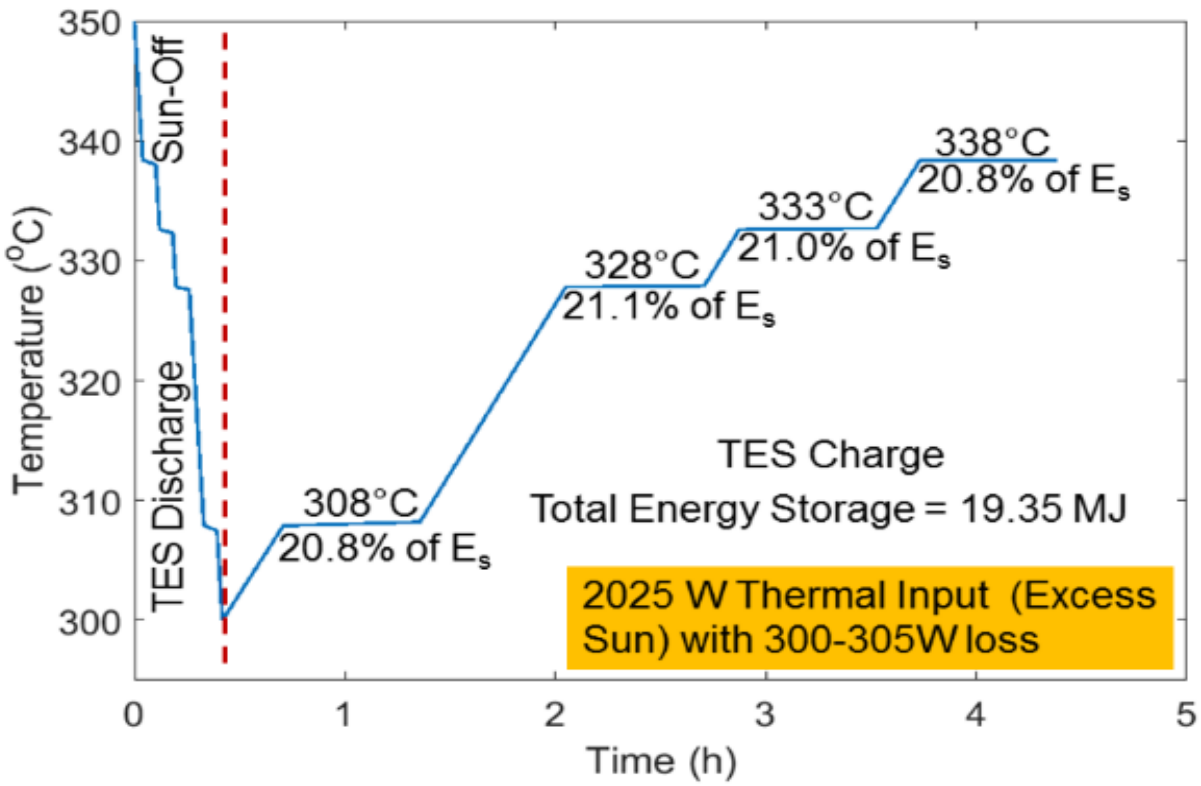
- Different Charge / Discharge Scenarios Considered
  - Fast Charge Scenario during initial charge-up in morning using full thermal input capability will create charge up time same as discharge time (~15 minutes)
  - Typical Mid-Day Re-Charge after short Sun-Off period (~15 minutes)

- Allows One to Charge / Discharge in Incremental Steps
- This Lowers the Total Thermal Exergy Loss in the Round-Trip Process
- Back to 90% Energy Storage in PCM with Higher Ultimate Storage Temperature
- Can Be Extended to More Stages, but Benefits Depend on Specific Designs, Thermophysical Properties, & Cost



Multiple Temperature-Staged Analysis

- Temperature staging of multiple TES materials does offer design and performance benefits as demonstrated in these analyses and results
- Requires judicious selection of TES materials with close consideration and matching of their thermophysical properties and phase change temperatures
- Thermal storage performance with multiple TES materials can store thermal energy at multiple temperature levels
  - Providing thermal exergy benefits
  - Storing more thermal energy between set thermal limits
  - Providing higher ultimate storage temperatures
  - Providing a "thermal switch" capability
    - Accommodate any runaway thermal excursions or extreme transients in Hybrid Solar Photovoltaic / Thermodynamic Power Cycle converter system.



Multiple Temperature-Staged Analysis

- Example: Four TES configurations were considered using 4 TES materials to establish temperature stages
- Latent and Sensible Heat entropy was evaluated using entropy equations shown in the paper
- Minimizing entropy depends strongly on material selections and their particular phase change temperatures

- Low Entropy Cases Also Have Highest Latent Heat Storage Fractions

	KNO3/KCl TES1	LiBr KBr TES2	FeCl2 NaCl KCl TES3	CaCl2 KCl LiCl TES4
Melting Temp (C)	307.8	327.8	332.6	338.4
Latent Heat (J/kg)	105630	333000	308880	241200
Solid CCP (J/kg-K)	1156	562	1326	950
Liquid CCP (J/kg-K)	1177	672	1695	1200
Mass TES (kg)	152.6	49	52.5	68

TES 23 & TES 234 Configurations Clearly Low Entropy Cases

	Total Energy Stored (MJ)	Latent Heat Storage Fraction (%)	Highest Latent Storage Temperature Obtained	Latent Heat Entropy-Eq.7 (J/K)	Sensible Heat Entropy-Eq.6 (J/K)
TES 23	17.86	0.9107	332.6°C	0.083	6482
TES 34	18.83	0.8584	338.4°C	~0.1	7916
TES 234	18.23	0.8897	338.4°C	0.174	6716
TES 1234	19.35	0.8369	338.4°C	0.315	8164

Key Exergy Optimization Design Parameters

- The TES optimization process is completely controlled by:
  - $(C_{p,TES}/h_{lat,TES})$
  - $(C_{p,Naph}/h_{lat,TES})$ ratios
  - (m_{Naph}/m_{TES}) ratio
  - TES operating temperature of interest
  - Cost and safety of these different TES materials
- Lower $(C_{p,TES}/h_{lat,TES})$ and $(C_{p,Naph}/h_{lat,TES})$ ratios leading to lower entropy generation (lower exergy) designs.
- This TES optimization process is then tempered by the critically important cost and safety considerations of the various TES options.
- Initial system-level models and analyses have provided critical design sizing information and demonstrated key thermal performance sensitivities associated with the current hybrid power system.

Fraction of Carnot Efficiency

$$\eta_{frac-Carnot} = 1 - \left[\frac{C_{p,TES}}{h_{lat,TES}} + \left(\frac{m_{Naph}}{m_{TES}} \right) \cdot \left(\frac{C_{p,Naph}}{h_{lat,TES}} \right) \right] \cdot \left(T_f - T_i \right)$$

Final Thoughts & Conclusions

- NASA Solar Power System work provides direct technology pathway to terrestrial "Energy Harvesting" solar power systems - Maybe a 10-20 Year Lag – Getting Shorter Every Year
- Solar array systems used out to Jupiter so far
- Spectrum splitting technology required to enable full spectrum capture - Being developed and refined
- Advanced TES systems and technology required to increase dispatchability and lower LCOE - Being developed and refined for terrestrial applications
- Terrestrial Solar Power Has Many Different Requirements from Spacecraft Systems
  - Cost is Always An Issue
  - Space Environments More Extreme Than Terrestrial (Hot - Venus & Cold – Mars & Beyond)
  - Terrestrial Applications Have Severe Cost & Environmental & Thermal Cycling Requirements
    - Spacecraft Solar Power System Materials in Large Quantities in Earth-Based Applications Can Sometimes Cause Severe Issues on Earth
- Goal is to Transition Terrestrial Power Advances Back into NASA Missions & Systems

Terrestrial Power Advances ⟷ NASA Mission Requirements

Expanding Our Energy Toolbox

Learn from the mistakes of others. You won't live long enough to make them all yourself.

Yogi Berra

Catch This Wave …… And **Ride** It!!

We Can Do This!! We Have the Tools and Knowledge!

This Too Can Be The Ride of Our Lives!!

AN ENERGY TSUNAMI AHEAD

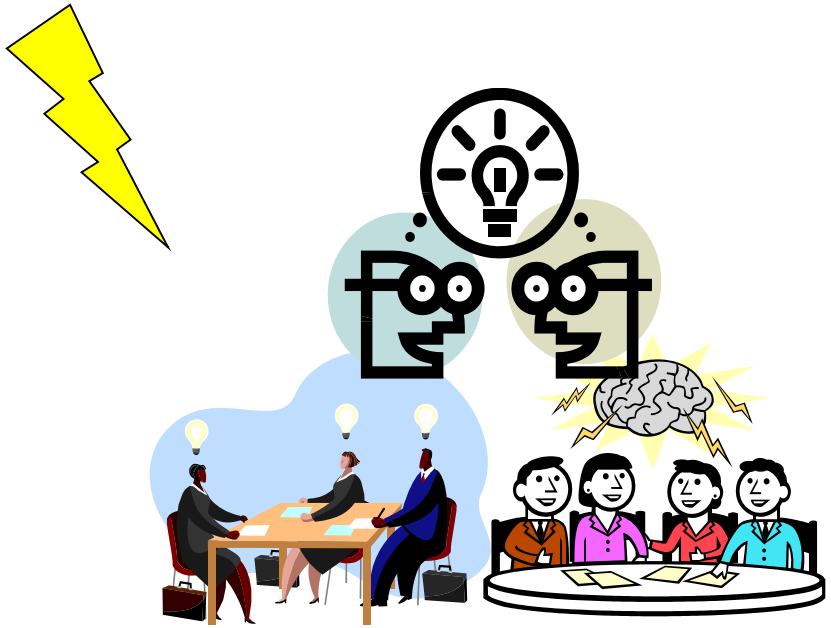
ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

Thank you for your interest and attention

Some People See the World as It Is and Ask Why…… I Dream What Has Never Been and Ask Why Not? Robert F. Kennedy, 1968

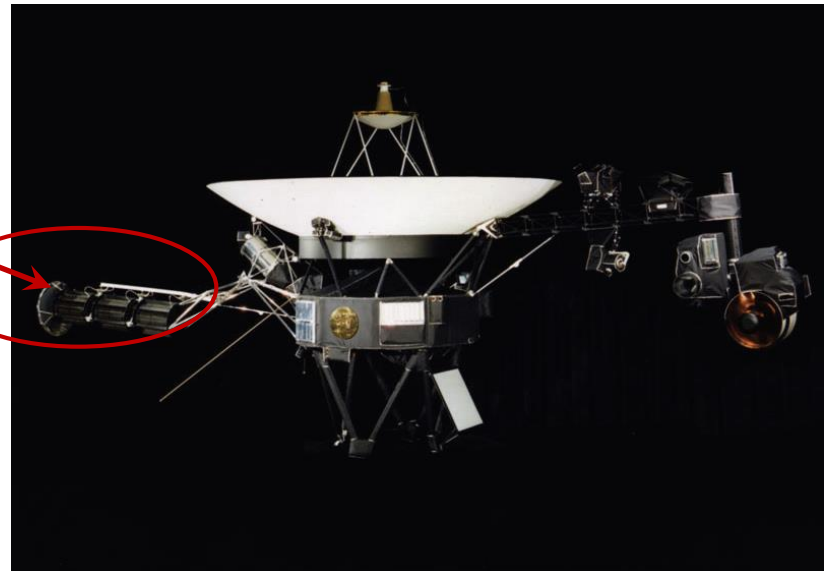
Questions & Discussion



BACKUP SLIDES

Voyager – Interstellar Mission (1977)

- Launched 37 Years Ago
- Traveled Farther than Anyone, or Anything, in History – 11 billion miles from Earth Now
  - First Spacecraft to Travel Beyond Our "Solar Wind"
- First Flyby Studies of Jupiter, Saturn, Saturn's rings, and the Larger Moons of the Two Planets, Neptune, Uranus
  - Discovered 3 of Jupiter's Moons – Adrastea, Metis, and Thebe
  - Detailed Investigation of Saturn's Rings
- Now in Interstellar Space Outside our Solar System
- RTG Power System (Based on Si-Ge Thermoelectric Materials)
  - Still Operating and Powering Spacecraft

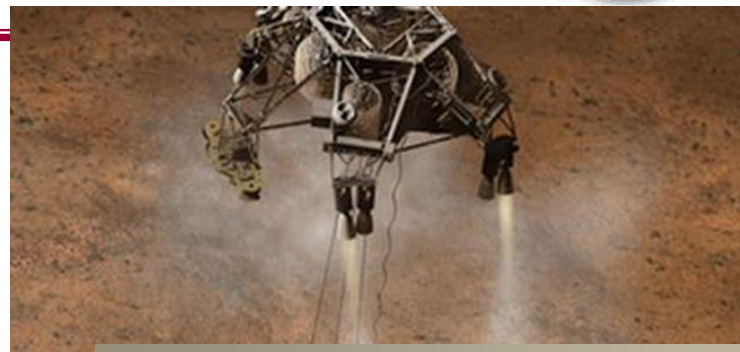


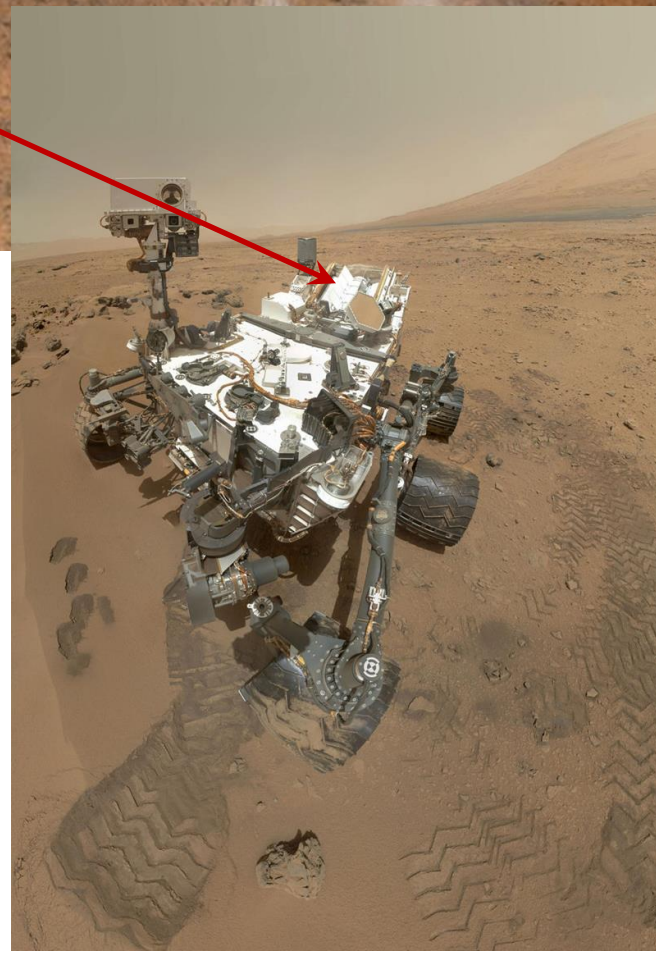
MARS SCIENCE LABORATORY (2012)

- Landed the Curiosity Rover on Mars in 2012 – Sky Crane
- About the Size of a Small Car (~2000 lbs)
- Radioisotope-Driven Thermoelectric Generator (RTG) Used to Power Curiosity
- Spent the Last 2 Years Investigating the Geology on Mars
- 1st Year on Mars - Discovered Strong Evidence of Prior Water on Mars
  - 3.5 Billi
  - Theory –
- Spent Last
  - 3-mile High Martian Mountain
  - Currently in the Foothills of Mt. Sharp
- Geology on Mars Similar to Earth

RTGs used successfully on 24 spacecrafts since 1961

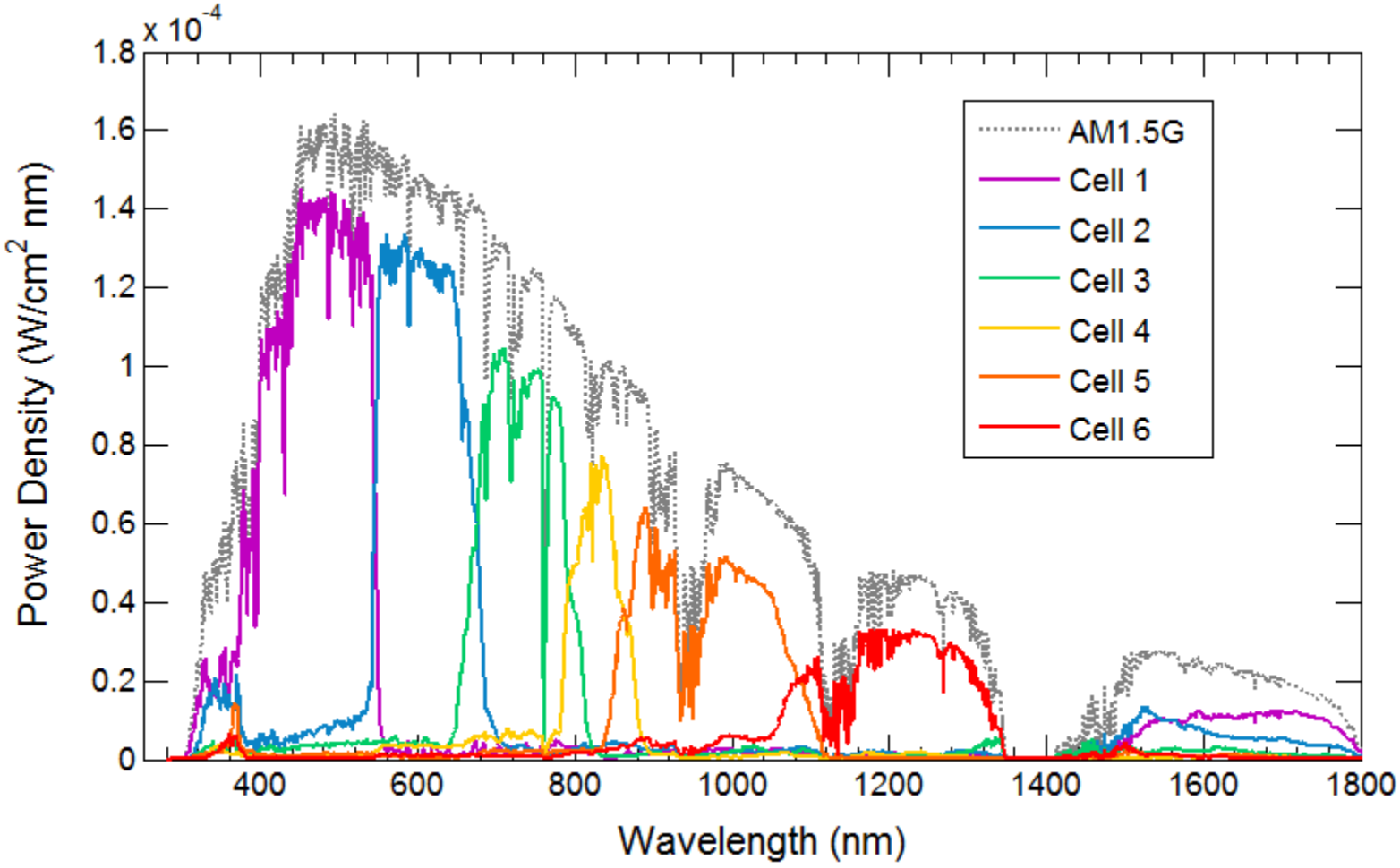
- **11 Planetary (Pioneer 10 & 11, Voyager 1 & 2, Galileo, Ulysses, Cassini, New Horizons)**
- **8 Earth Orbit (Transit, Nimbus, LES)**
- **5 Lunar Surface (Apollo ALSEP), 2 Mars Surface (Viking, MSL/Curiosity)**



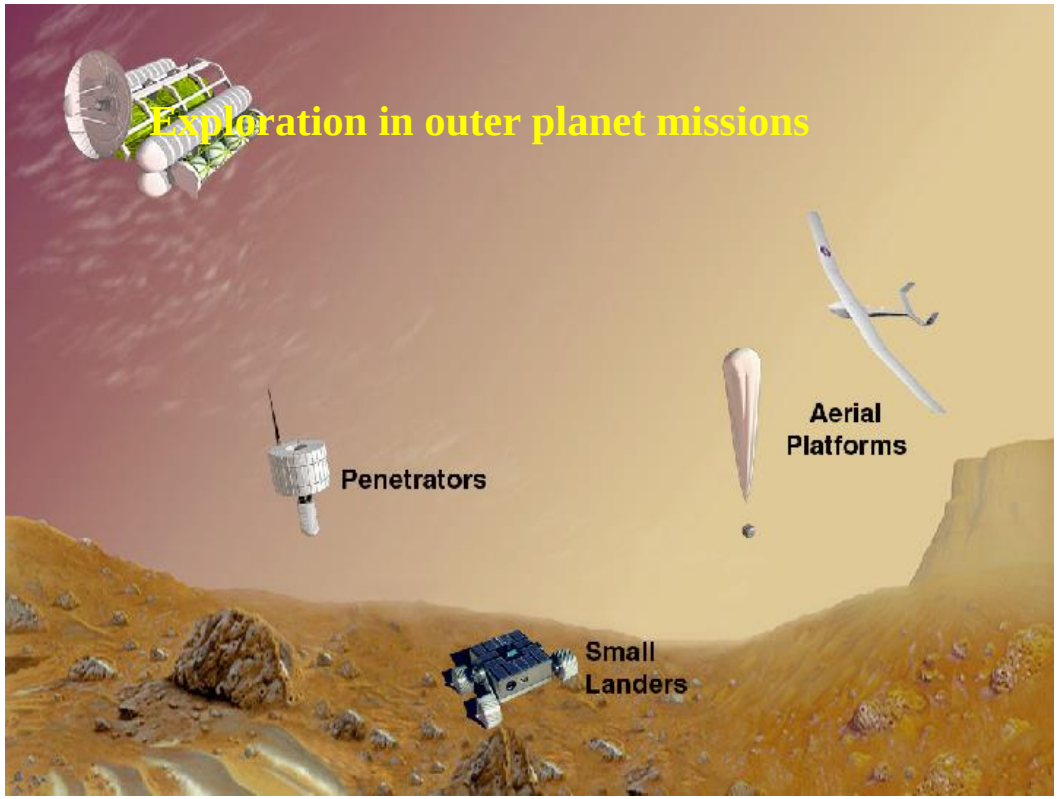


RTG Power With Heritage TE Materials Made this All Possible
TAGS, PbSnTe, PbTe TE Materials – Segmented Elements

Polyhedral Specular Reflector Prototype Spectra



Caltech

Low-Power Energy Harvesting Systems for Outer Planets Mission Concepts

- **Outer Planets exploration activities**
  - Through ice, water, cryogenic liquids, hot gases, high g loads, moderate to high radiation
  - Such as for Europa landers, Titan explorers, Comet sample return vehicles…
- **Need for miniaturized robust power sources**
  - To enable/prolong planetary exploration, to permit novel/more science measurements
  - To enable development of novel miniaturized autonomous probes such as drop-off penetrators, weather microstations, communication relay devices, etc…