Energy Harvesting: Unique Systems from Earth to Planets to Deep Space and Beyond – Building & Expanding Our Energy Toolbox

presented at

McMaster Institute of Energy Studies

McMaster University

Energy Mixer Seminar

Hamilton, Ontario, Canada

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

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

MMRTG Pyroshock/JPL MATRIX Project Manager

Jet Propulsion Laboratory, California Institute of Technology

Pasadena, California, USA

20 April 2016

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

AGENDA

- Recent Spacecraft Power Systems
- Terrestrial Waste Energy Recovery Applications
  - Motivations
  - Automotive Energy Recovery Systems
  - Industrial Energy Recovery Technologies
  - Aircraft Energy Recovery
  - Full Spectrum Solar Energy Utilization (Waste Heat Here Too)
- Final Thoughts

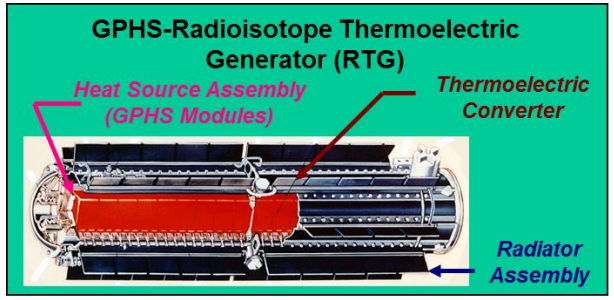
NASA Science Exploration Missions Need for Both Solar & Radioisotope Power Systems (RPS)

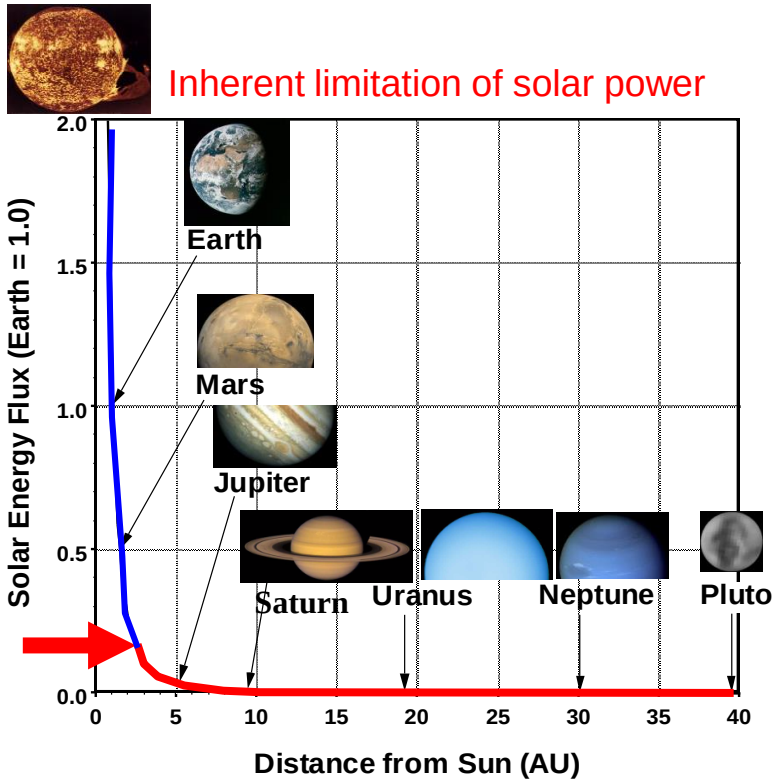
Solar power systems serve a *critical role* in the scientific exploration of the near-Earth solar system

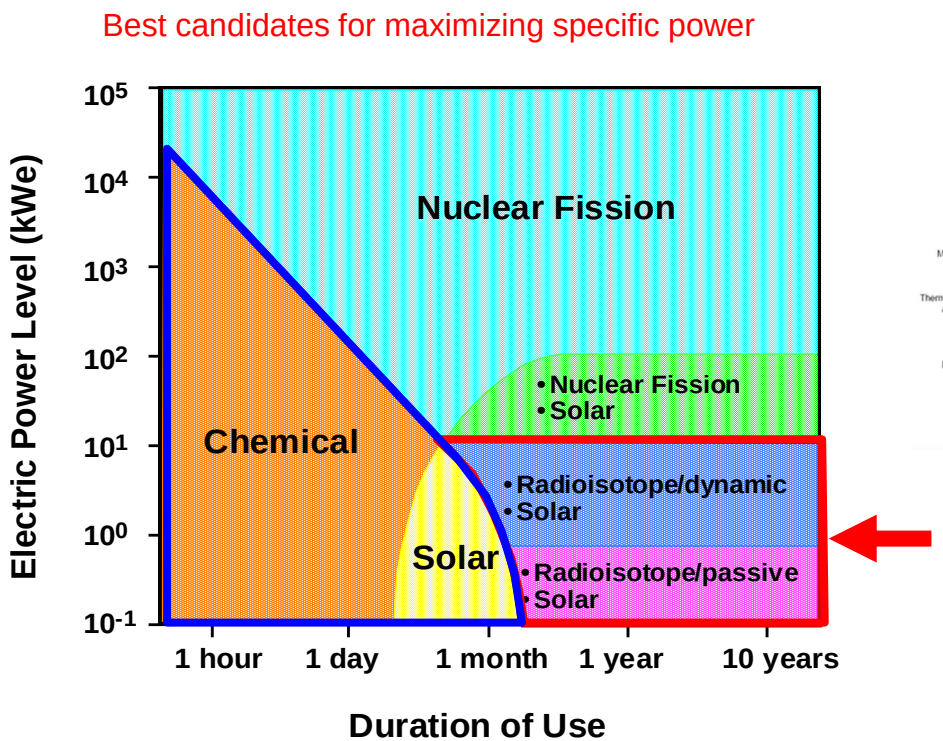
- Moderate power levels up to 100 kW
- Operations dependent on distance and orientation with respect to Sun

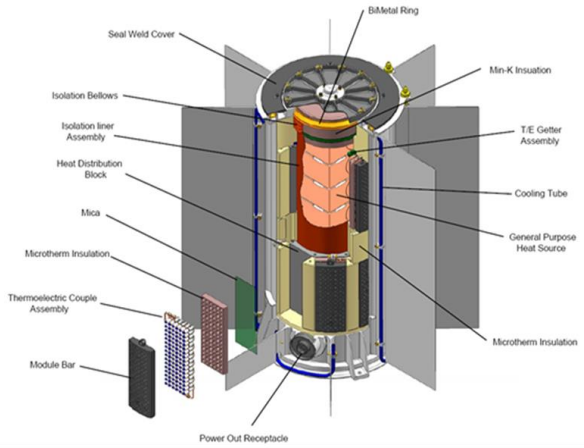
Radioisotope power systems (RPS) serve a *critical role* in the scientific exploration of the deep-space solar system

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





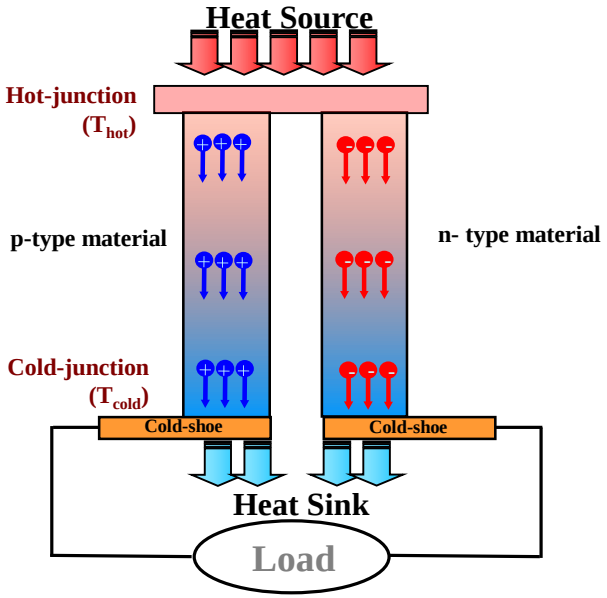




Multi-Mission RTG

Thermoelectric Power Generation

Thermoelectric Couple

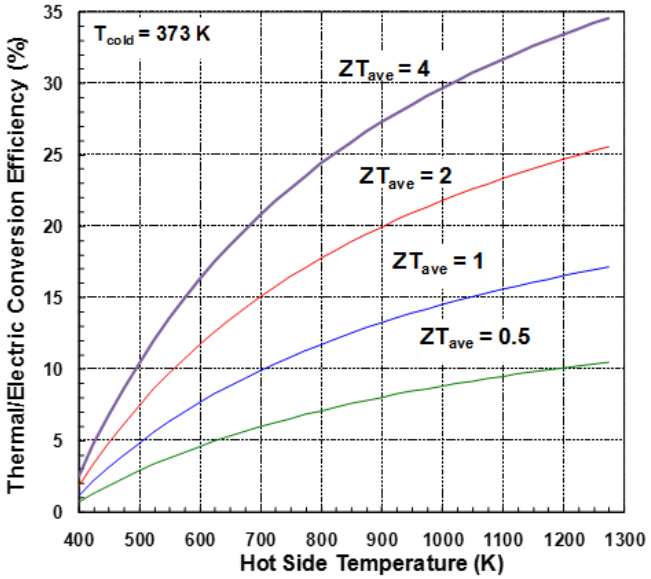


Thermoelectric effects are defined by a coupling between the electrical and thermal currents induced by an electric field and a temperature gradient

Dimensionless Thermoelectric Figure of Merit, ZT

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

Seebeck coefficient S
Electrical conductivity σ
Electrical resistivity ρ
Thermal conductivity λ
Absolute temperature T



Conversion Efficiency

Common TE Materials:

Bi_2Te_3 300 K – 525 K
PbTe-based 400 K – 775 K
SiGe-based 525 K – 1273 K
Skutterudites 475 K – 875 K
$La_{3-x}Te_4$/Zintls 625 K – 1273 K

Power generation
(across 1275 to 300 K)
State-Of-Practice materials:
$ZT_{average} \sim 0.5$

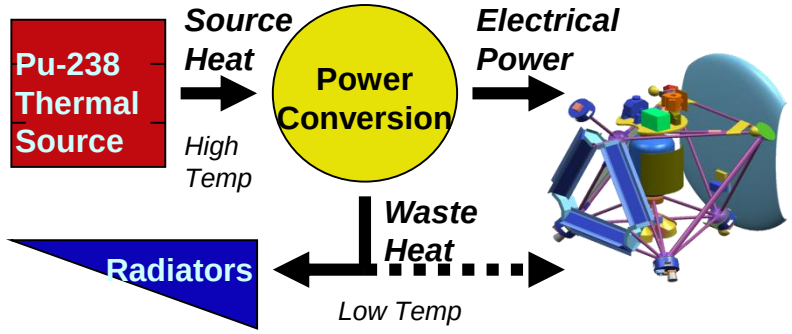
State-Of-the-Art materials:
$ZT_{average} \sim 1.1$

Best SOA materials:
$ZT_{peak} \sim 1.5$ *to* 2.0

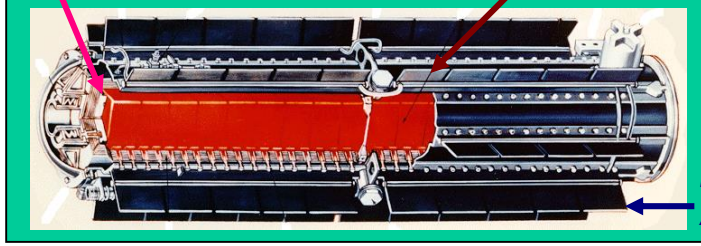
Conversion efficiency is a direct function of ZT and ΔT

Overview of a Radioisotope Power System

- **High grade heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
  - 87.7-year half-life
  - Heat source temperature ~ 1300 K
- **Portion of heat energy converted to electricity via passive or dynamic thermal cycles (6%-35%)**
  - Thermoelectric (existing & under development)
  - Stirling (under development)
  - Thermophotovoltaic, Brayton, etc. (future candidates)
- **Waste heat rejected through radiators or a portion can be used for thermal control of spacecraft subsystems**



GPHS-Radioisotope Thermoelectric Generator (RTG)



Performance characteristics

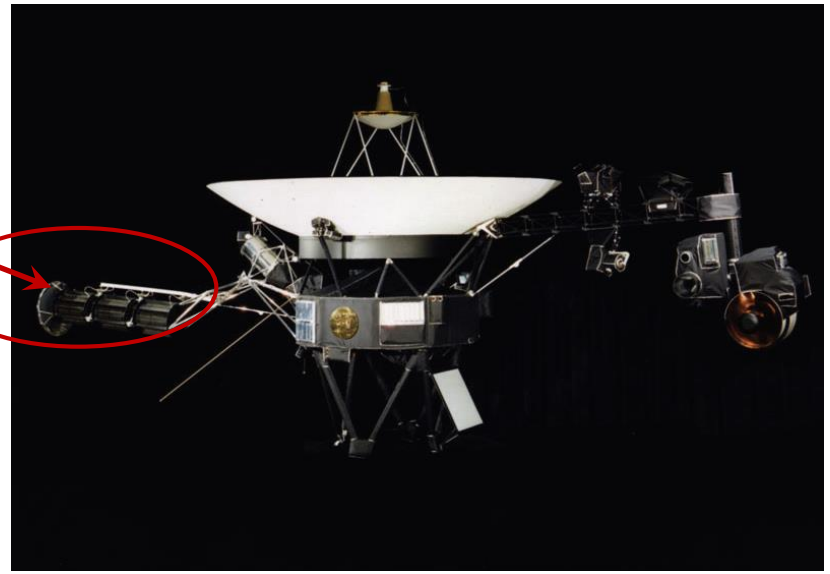
- Specific power (W/kg) → Direct impact on science payload
- T/E efficiency → Reduces PuO_2 needs
- Power output → Supports diverse mission profiles

RTGs used successfully on 27 spacecrafts since 1961

- 9 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)

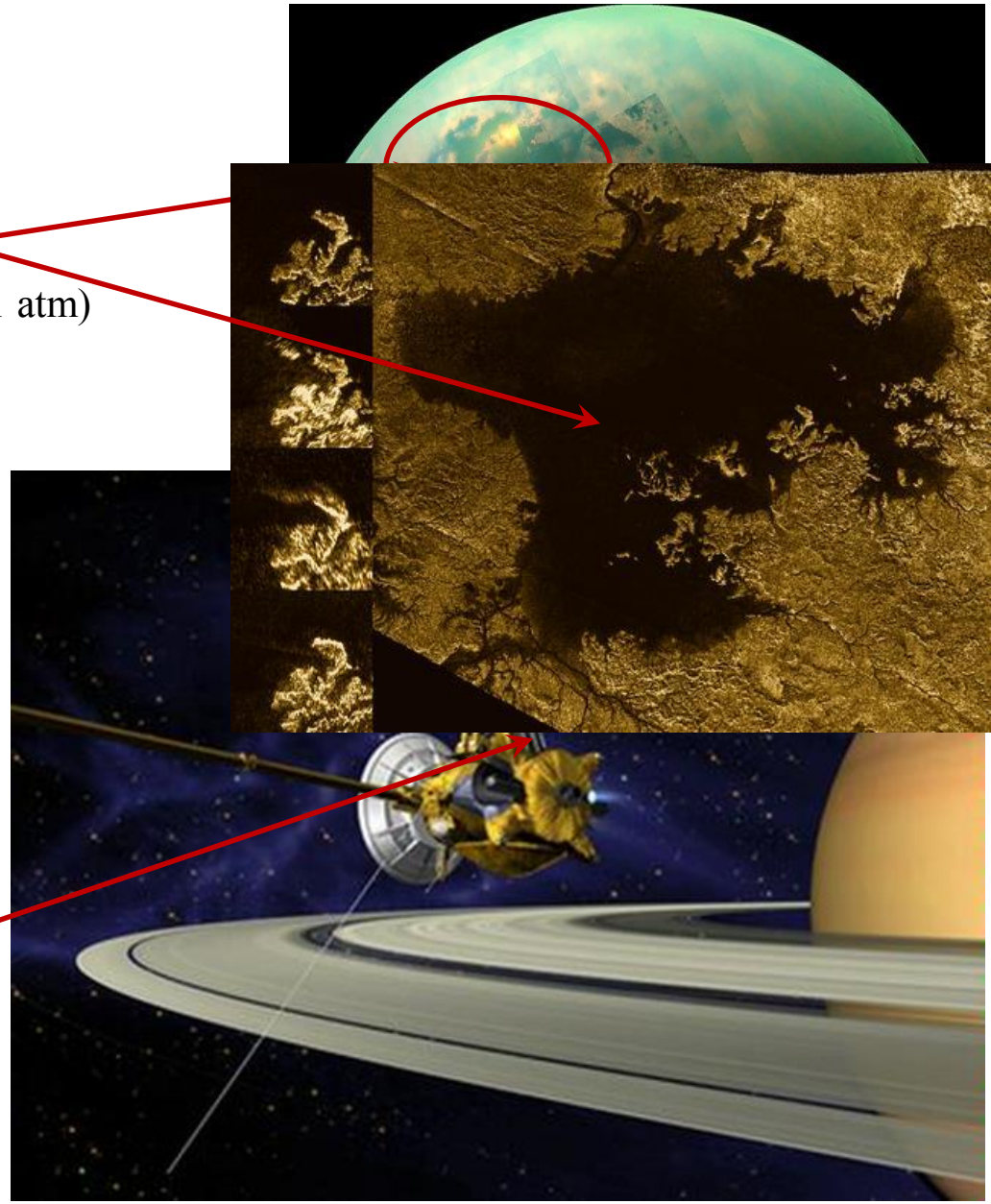
Voyager – Interstellar Mission (1977)

- 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



CASSINI Spacecraft to Saturn (1997)

- Vastly Updated Science on Saturn's Rings
- Incredible Science on Saturn's Moon Titan
  - Many Earth-Like Processes
  - Liquid Rivers & Lakes of Ethane & Methane Over Frozen Water
  - Ethane and Methane "Rains" in Atmosphere (Pressure Slightly Higher than ~1 atm)
  - Salty Brine Ocean Under Icy Crust
  - Liquid Water and Ammonia Ocean ~100km Below Frozen Crust
  - Methane Atmosphere ~5% Methane – Geologic Processes Replacing Methane
- Likewise, Saturn's Moon Enceladus
  - Liquid Water Beneath its Icy, Snowy Crust
  - Geologic Activity – Ice & Water Crystal Plumes at its South Pole



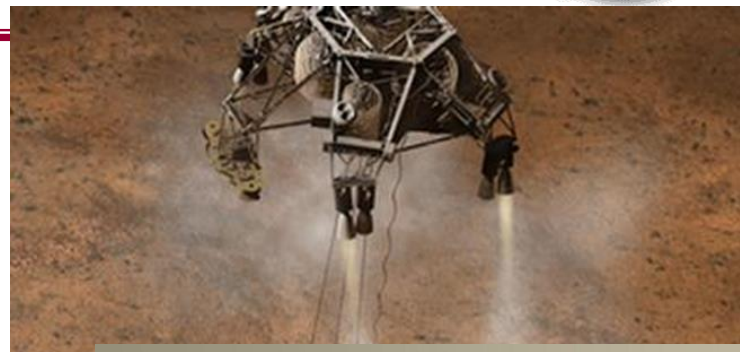
RTG Power Made this All Possible
SiGe TE Materials

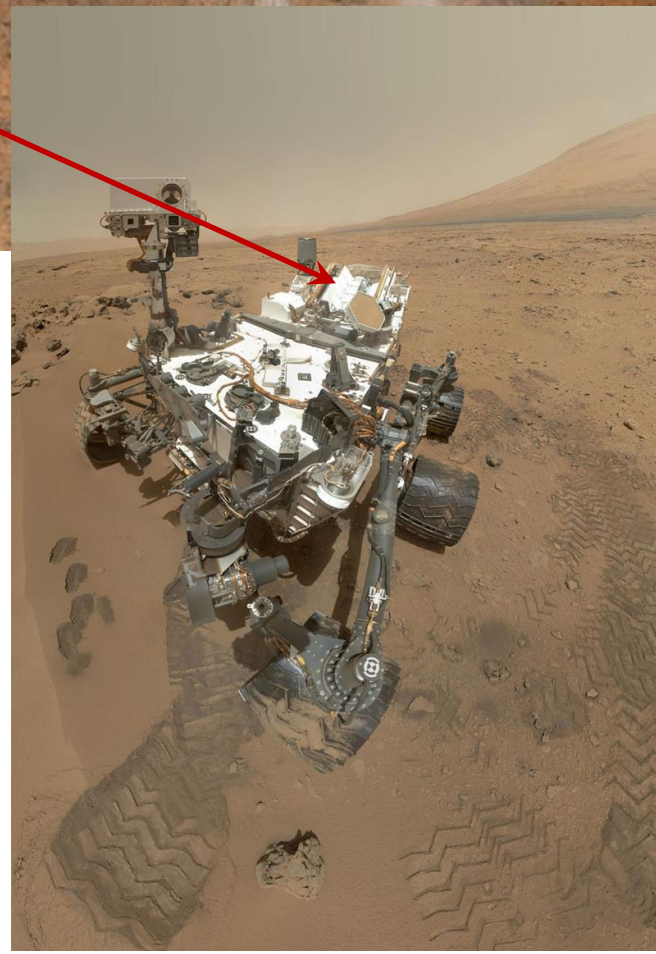
MARS SCIENCE LABORATORY (2012)

- 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
  - 3.5 Billi
  - Theory –
- Spent Last Year "Driving" from Landing Site to Mt. Sharp
  - 3-mile High Martian Mountain
  - Currently in the Foothills of Mt. Sharp
- Geology on Mars Similar to Earth

RTGs used successfully on 27 spacecrafts since 1961

- **9 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

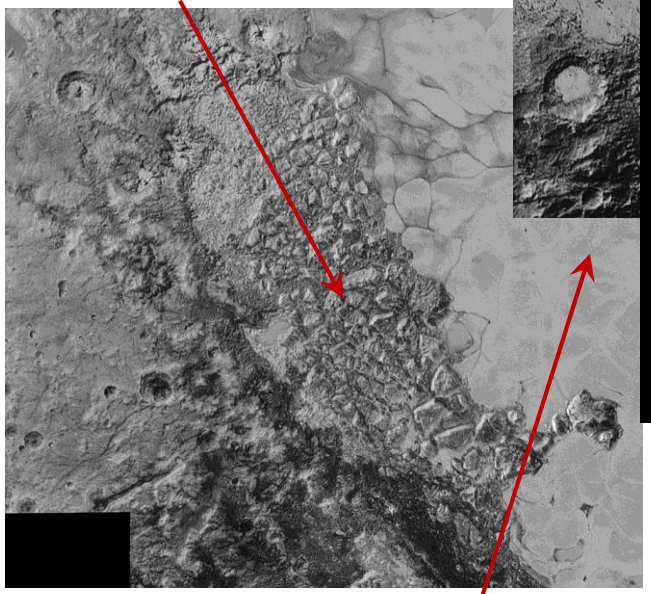
New Horizons to Pluto (2006)

Heart of Pluto

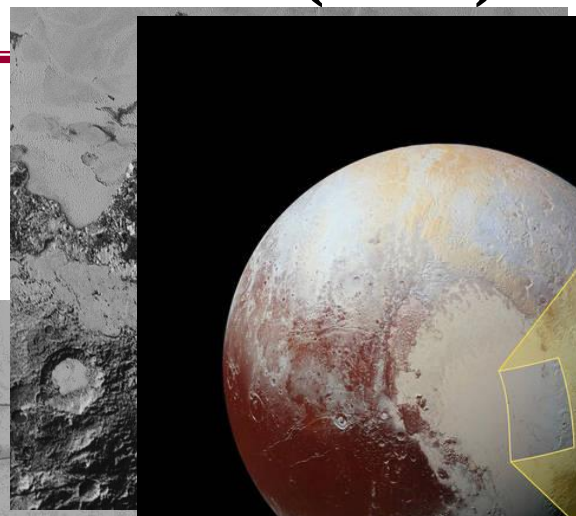
With Love,
Pluto

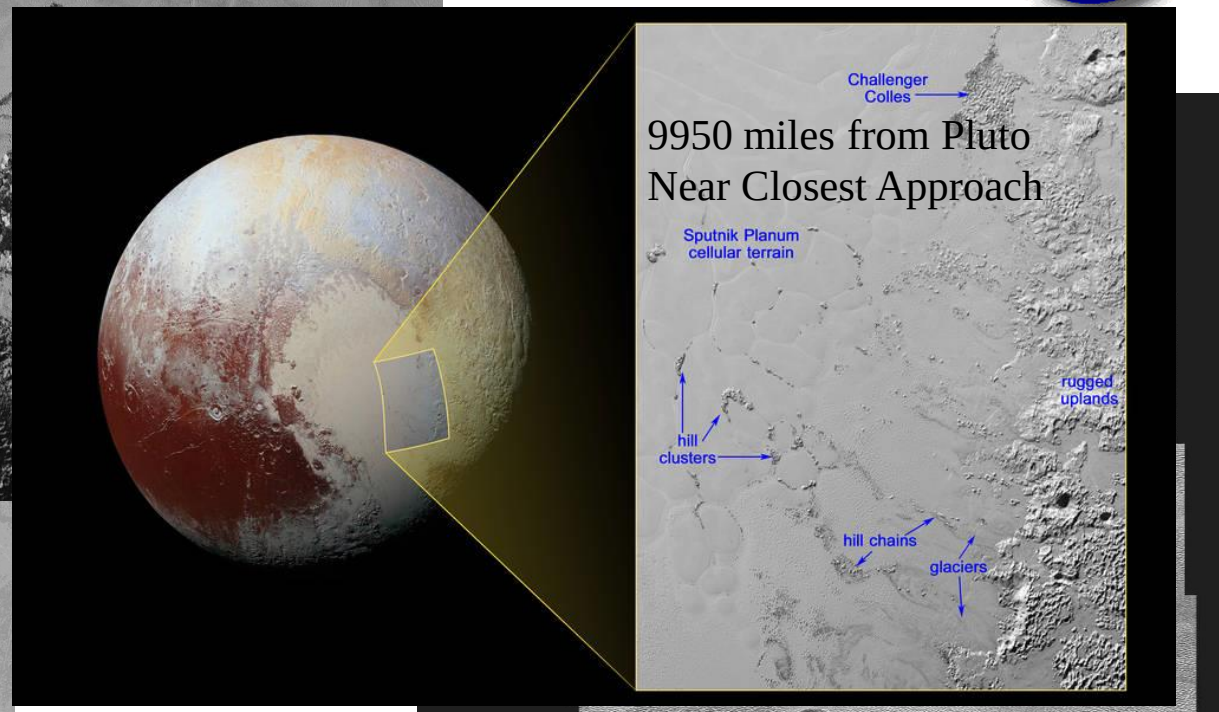
476,000 miles from Pluto

Large region of jumbled, broken terrain



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





10,000 miles from Pluto

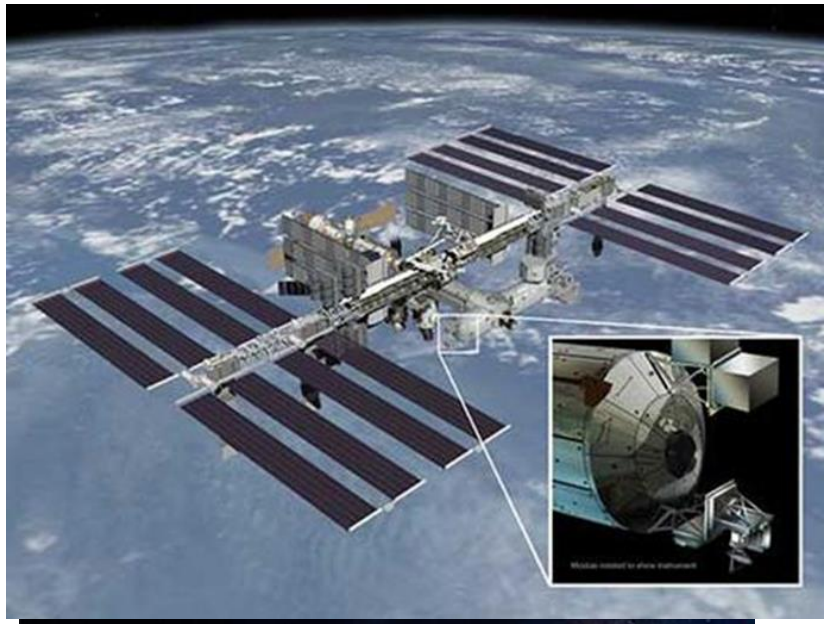
RTG Power Made this All Possible
SiGe TE Materials

300 mile wide image, smallest features 0.5 mile wide

Water ice hills are floating in a sea of frozen Nitrogen

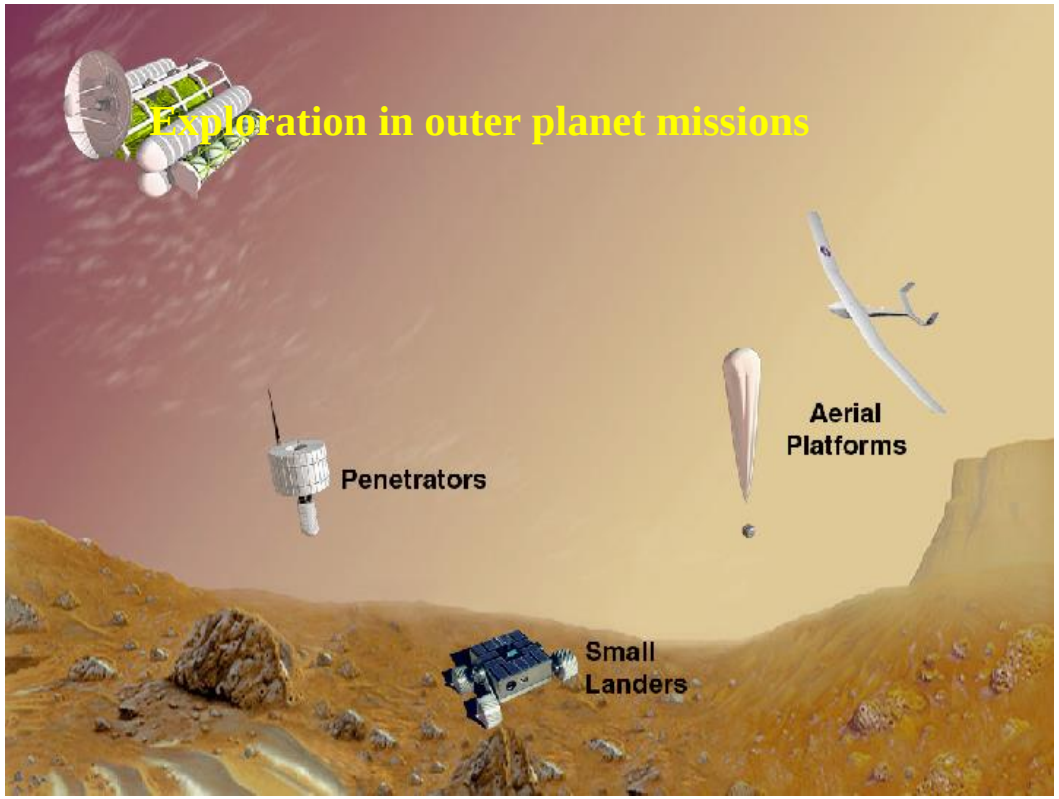
SPACECRAFT SOLAR SYSTEMS
INTERNATIONAL SPACE STATION & DAWN

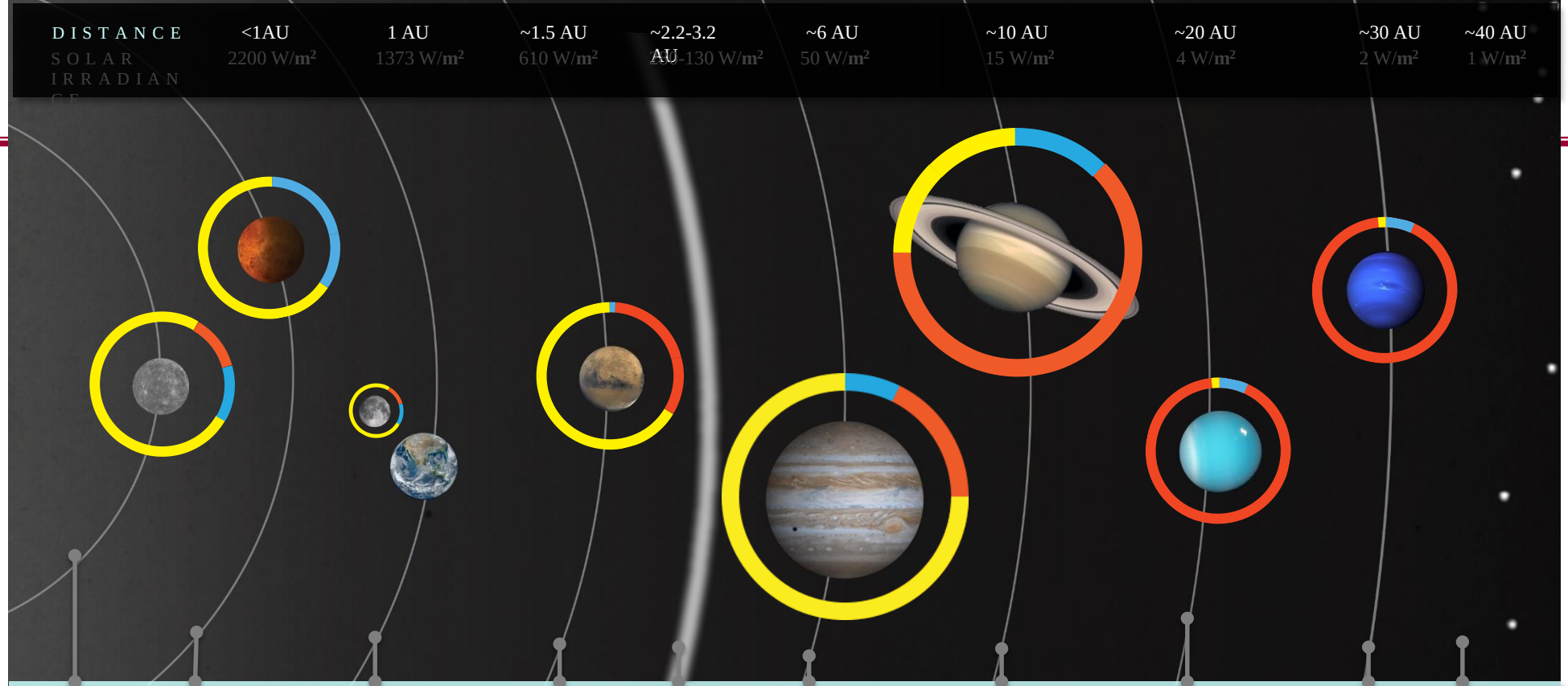
- Solar Photovoltaic Power System Used to Power Current International Space Station
  - Silicon
  - Eight 375 m^2 Solar Arrays, 84 – 120 kW
- Dawn Spacecraft
  - Asteroid Chasing - Vesta and Ceres Asteroids
  - Hyper-efficient Ion-Propulsion (Xenon fueled)
  - 10 kW of Solar Power @ 1 A.U.; 1.3 kW @ 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
  - Arrives July 2016
  - Study Jupiter Atmosphere, Magnetic, & Gravity Fields



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…





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

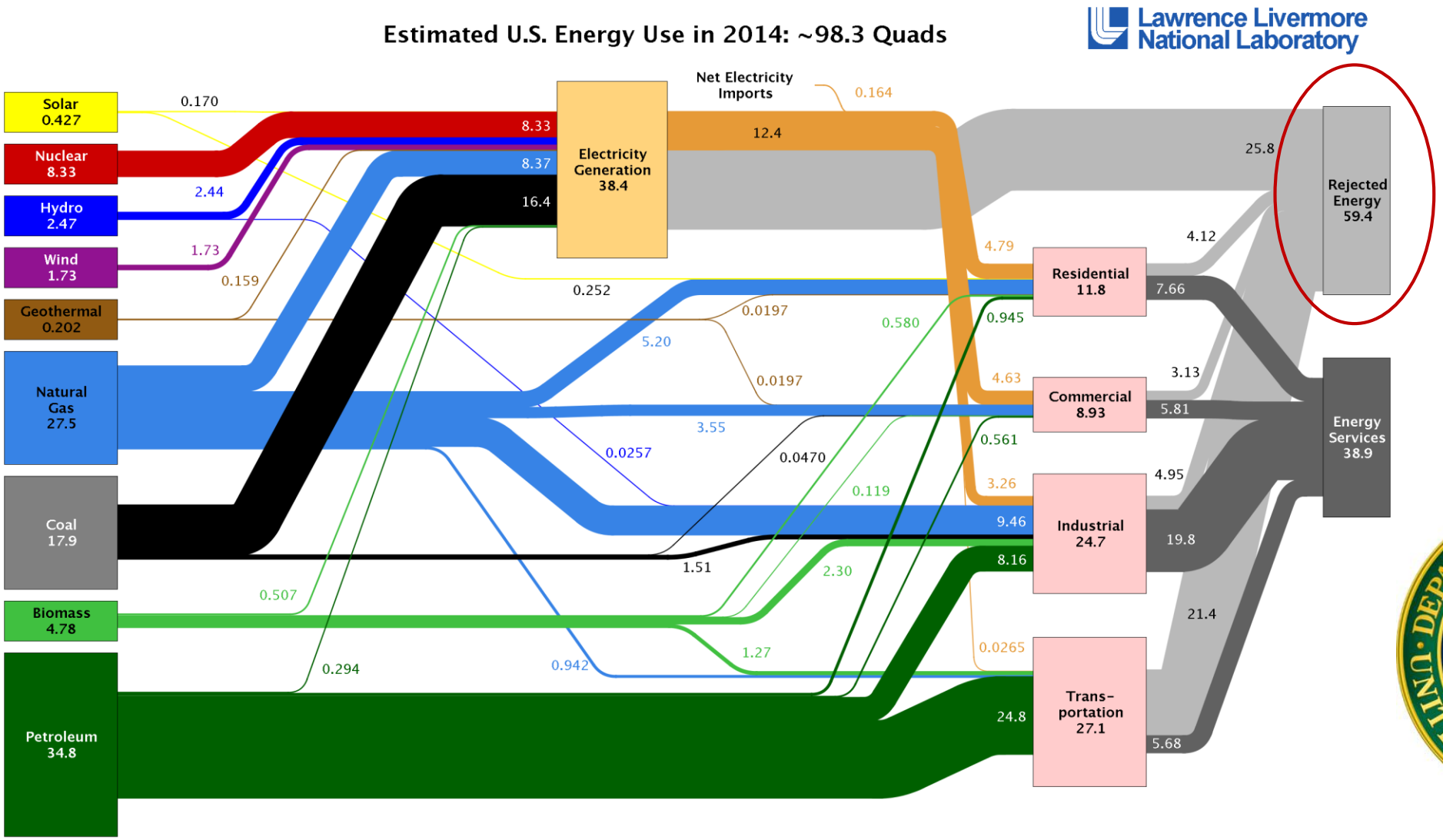
Looks Like Space to Me!!

[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% for the 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

U.S. National Waste Energy Recovery

- **Transportation Sector**
  - 12.5 Quads
  - Light-Duty Passenger Vehicles + Light-Duty Vans/Trucks (SUVs)[1]
  - Medium & Heavy-Duty Vehicles[1]

- **Industrial Process Sector is Another Opportunity**
  - 5-10 Quads of Waste Energy Flows in Industrial Processes
    - Aluminum, Glass
    - Paper
    - Petroleum
    - Chemical
  - 1.8 Quads Recoverable, Potentially 1.56 GW[2]
  - Wide Range of Temperatures & Heat Sources

- **Europe and Asia Have Similar Challenges**

Waste Energy All Around Us

[1] *Transportation Energy Data Book*, 2010, Edition 29, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicles Technology Program. ORNL-6985, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cta.ornl.gov/data/index.shtml.

[2] U.S. Energy Information Agency, 2007 Annual Energy Outlook

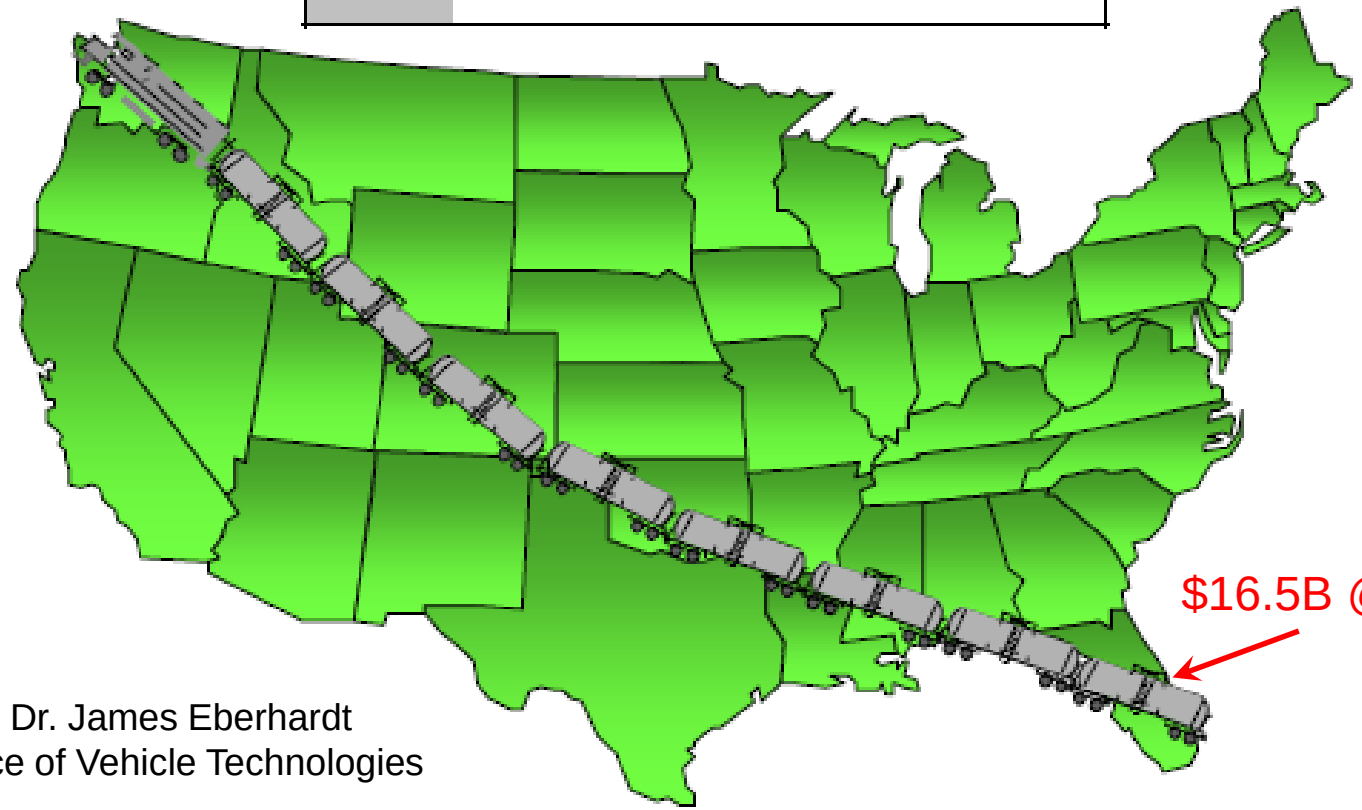
The Magnitude of Our Energy Problem

Office of Heavy Vehicle Technologies

	1973	1997
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

2014
~98.3 Quads[1]

[1]U.S. Energy Information Agency



$16.5B @ $50/Barrel

Reference - Dr. James Eberhardt
DOE – Office of Vehicle Technologies

1 Quad of energy is equivalent to 340,000 tank cars of crude oil stretched from Miami to Seattle (3,300 miles).

Environmental Effects Are Strongly Tied to Our Energy Use

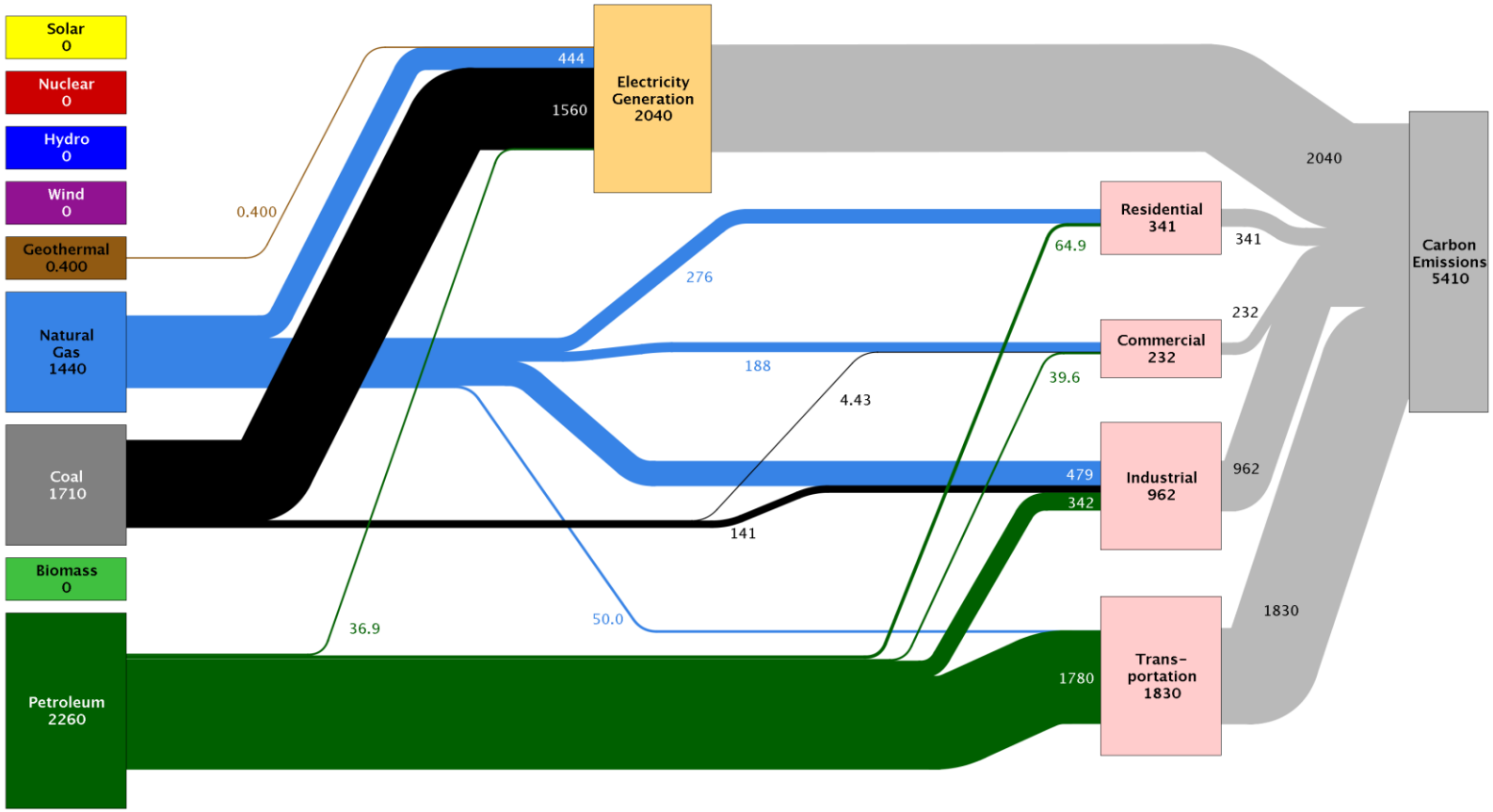
- ~1 kg of CO_2 produced per 1 kWhr (Coal Produced Power)
- ~0.5 kg of CO_2 is produced for 1 kWhr (Natural Gas Power)

Down ~400 Million Metric Tons From 2008
Mostly from Reduced Coal & Petroleum Use

* Methane is the world's most abundant hydrocarbon. It's the major component of natural gas and shale gas and, when burned, is an effective fuel. But it's also a major contributor to climate change, with 24 times greater potency as a greenhouse gas than carbon dioxide.

Estimated U.S. Carbon Emissions in 2014: ~5,410 Million Metric Tons

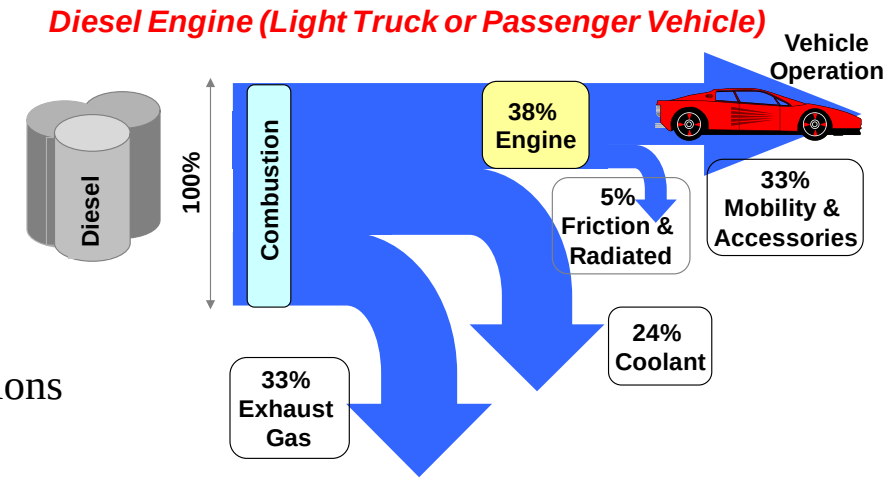
Lawrence Livermore National Laboratory

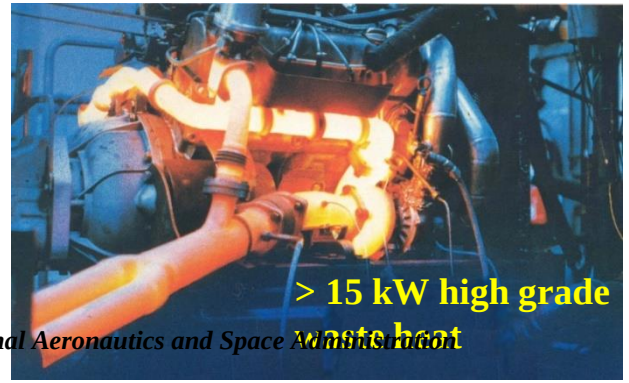


Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2015. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combusition of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

TE for Vehicle Energy Harvesting & Utilization

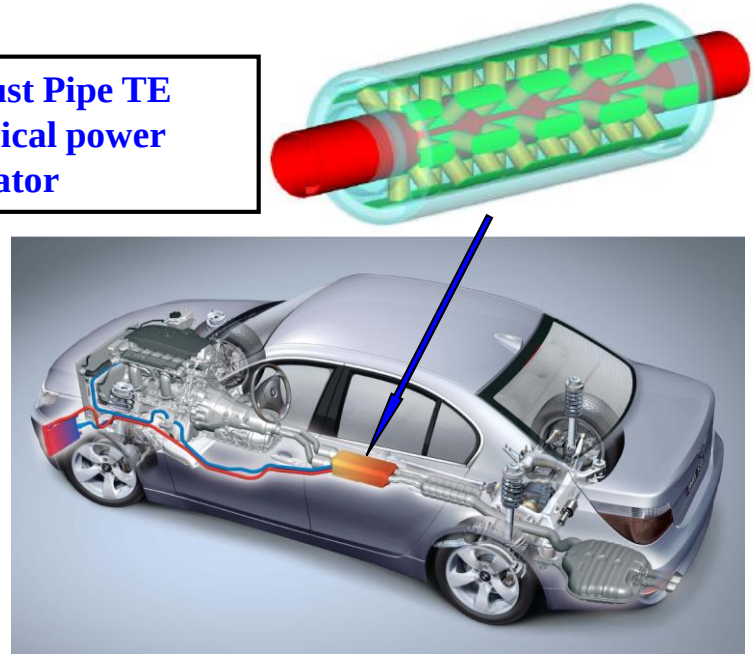
- Thermoelectrics in Vehicles
  - TE has unique advantages for integration
  - Reliability, Modularity, Compactness
- What has been done?
  - U.S. DOE & U.S. DoD Projects
  - Low efficiency Bi_2Te_3-based TE generators (TEG) demonstrations
  - Higher efficiency Skutterudite & LAST/LASTT module demonstrations
  - ~650 W Systems Demonstrated
- What is needed?
  - Increase TEG operating temperatures, ΔT
  - Integrate higher ZT materials (ZT_{ave} ~ 1.5 to 2)
  - Develop and scale up HT TE module technology
  - Integrate with efficient heat exchangers





~2-3% Fuel Efficiency improvement with exhaust waste heat recovery

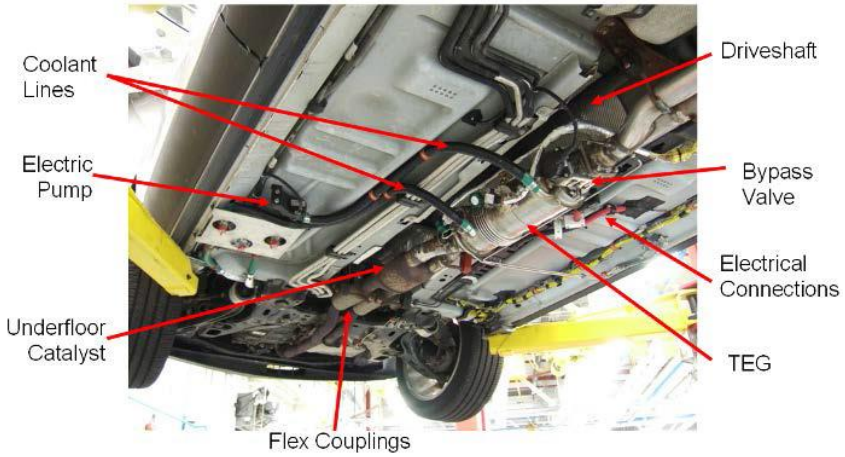
Exhaust Pipe TE Electrical power generator

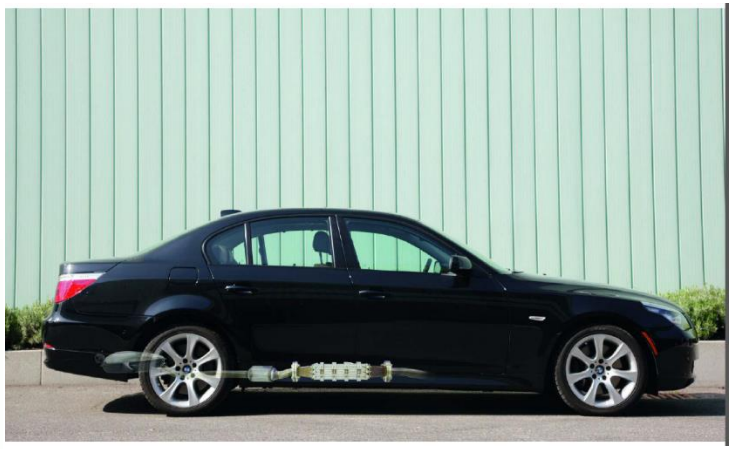


Thermoelectrics in a Ford Lincoln MKT & BMW Series 6 (May 2012)

- Demonstrated 450 W Power Output on a BMW Drive Cycle at 130 kph
- Demonstrated 300 W Power Output on a Ford Lincoln MKT at 65 mph

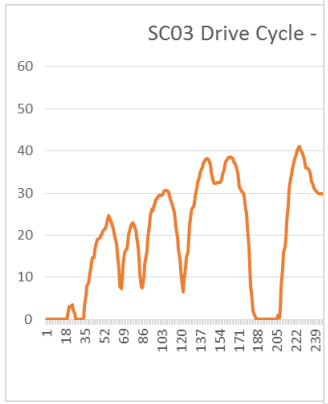
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/adv_combustion/ace080_lagrandeur_2012_o.pdf

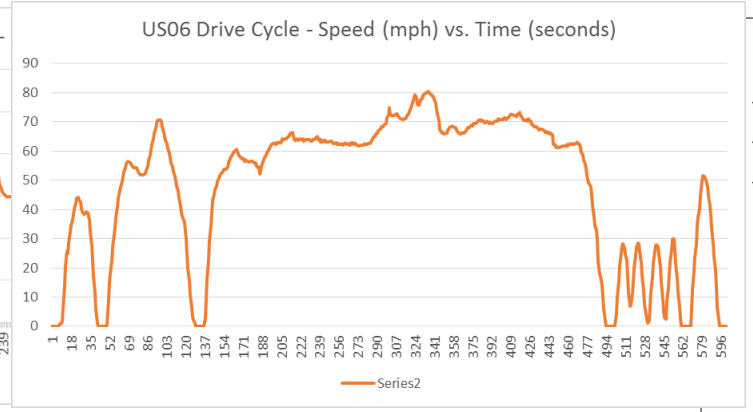


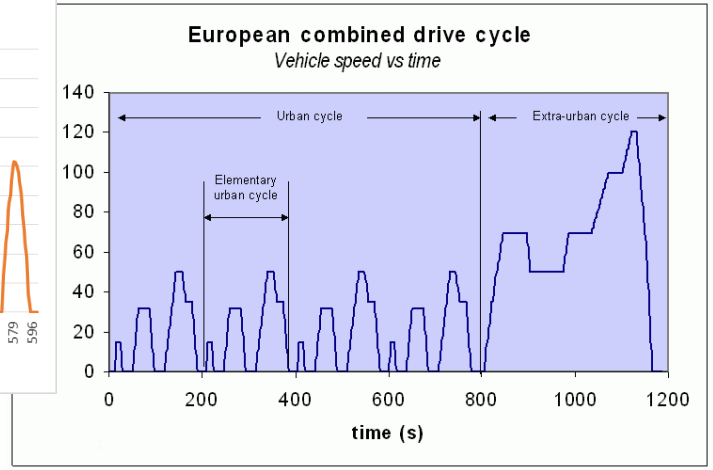


https://www1.eere.energy.gov/vehiclesandfuels/

- BMW ultimately interested in average power over NEDC
- Ford and U.S. Auto Companies ultimately interested in US06 & SC03







Drive cycle contained in UN/ECE Regulation 101

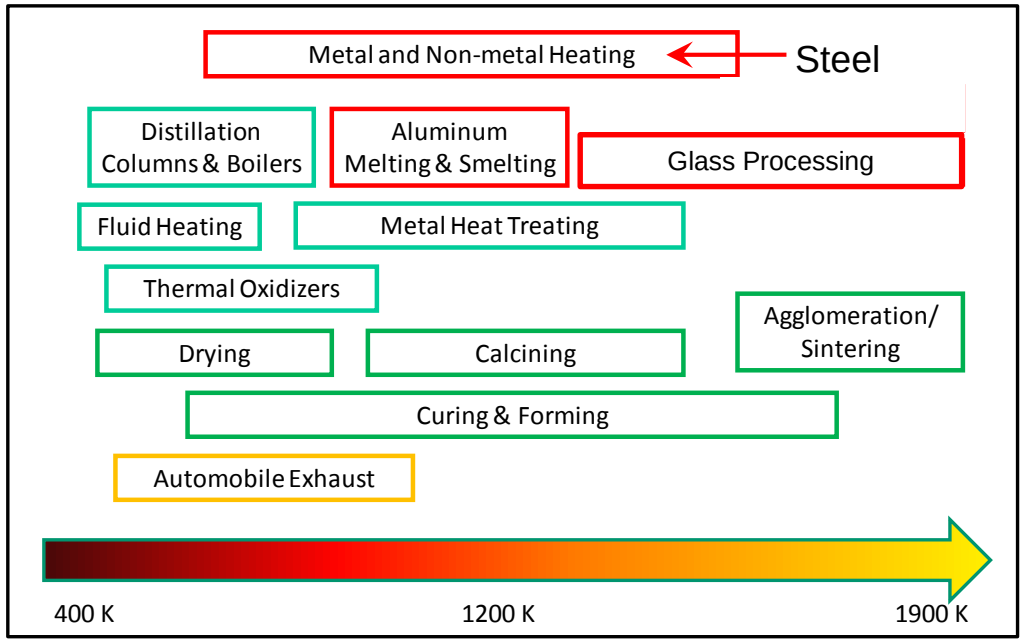
Terrestrial Industrial Process Waste Heat Recovery

- System Solutions Needed to Recover Energy Throughout the Industrial Processing Complex
  - Produce Power
  - Residential & Commercial Space Heating
  - Radiant Collectors, Rankine cycles, Stirling cycles, & Thermoelectric Conversion
  - High-Temperature TE & Structural Materials and Systems; High Temperature Thermal Energy Storage
- Steel Industry
  - Electric Arc & Blast Furnaces, Steel Slabs, Slag By-Products
  - 10's of Megawatts of Thermal Energy Available in Each Potential Location in Steel Processing
  - Process Temperatures Available: 200-1000°C
  - 13 GW Total Potential Power Production in U.S. Alone
- Various Other Industrial Processes
  - Glass Furnaces, Aluminum Processes, Petro-chemical All Have Common Requirements
  - Process Temperatures Available: 760 – 1400°C
  - Another >39 GW Potential Power Production in These Industries in U.S.
  - Large International Interest in WHR Systems
    - Latest International Conference on Thermoelectrics 2015, Dresden, Germany
    - Energy Harvesting - 2014 U.S. Emerging Technology Conference & Exhibition, Santa Clara, CA

www.dpp-Europe.com

Industrial Energy Recovery Projects

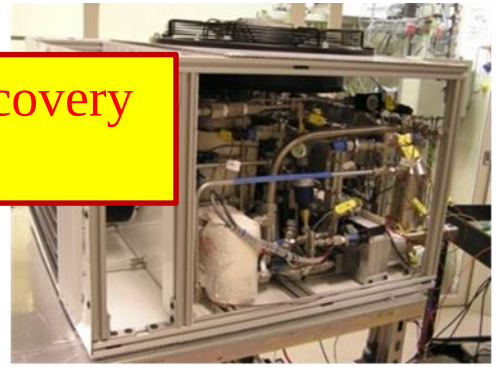
- Project Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
- Critical Peripheral Benefits Also Surface Beyond These Savings
  - Improved Product Quality (PACCAR Kenworth)
  - Improved Safety (Less Indoor Air Pollution)
  - Enhanced Product Throughput Due to Process Efficiency Increases
  - Enhanced Operational Efficiency (Less Water Use)
- Challenges:
  - Scaling Up to Industrial Processing Energy Flows
  - System Cost and Payback
  - Integrating into Industrial Processes Without Adversely Impacting Product Quality and Critical Metrics
  - High-Temperature Materials – Durability and Operational Maintenance
    - $La_{3-x}Te_4$, Zintls, Skutterudite TE Materials are One Solution
  - In Some Cases, Similar Source Temperature and Energy Flow Variability as in Automobile Applications
  - "Occupied" Volume and Compactness
    - JPL Working on Higher Power Density TE Solutions in Automotive and DARPA Programs



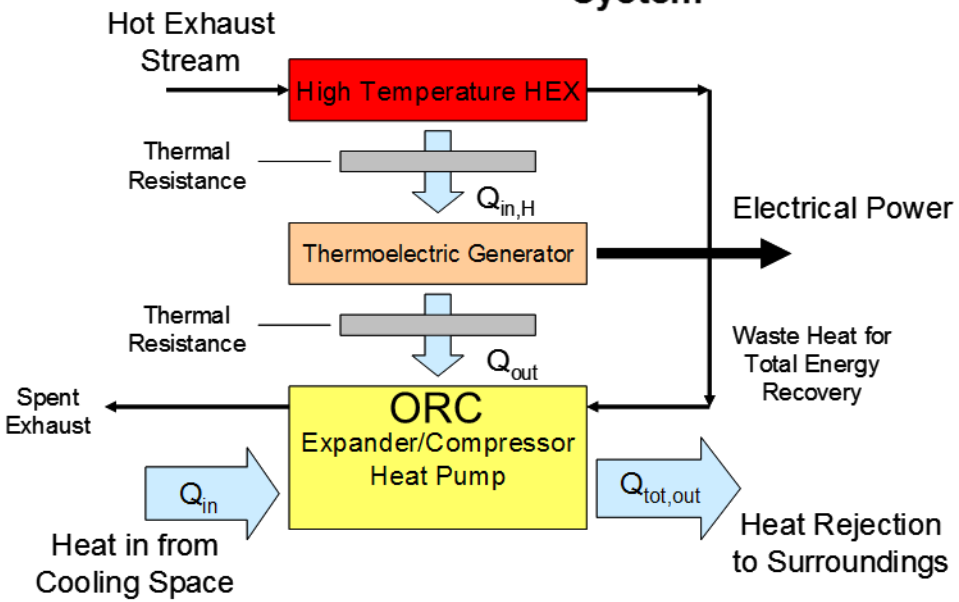
Hybrid Thermoelectric / Organic Rankine Cycle System

- Leverage Spacecraft/Defense Technologies & Expertise to Commercial Energy Recovery
  - One I
  - Co-G
    - 1
    - Next Logical Step is to Scale Up to Larger Army, Navy, and Commercial Waste Heat Recovery Applications
  - Sophisticated Energy Recovery System for Army Heavy Vehicles & DoD Facilities
    - Simultaneous Power & Cooling
    - Thermoelectric Topping Cycle
    - Organic Rankine Cycle (R-245fa Working Fluid)
    - Several Micro-Technology Heat Exchangers
  - Successfully Designed, Fabricated and Tested in 2008-2011[1,2]
- Benefits & Mission Relevance
  - Reduce Fuel Usage ~20% in Army Forward-Deployed Applications
  - Utilizing a "Free" Resource
  - Energy Efficiency in Vehicles & TQG's to Reduce Nation's Oil Dependency
  - Reduced Emissions
- Other Hybrid TE / Thermodynamic Cycle Systems Being Explored

Prototype Hybrid Power/Cooling System with Commercial Waste Heat Recovery Applicability Demonstrated to TRL 4



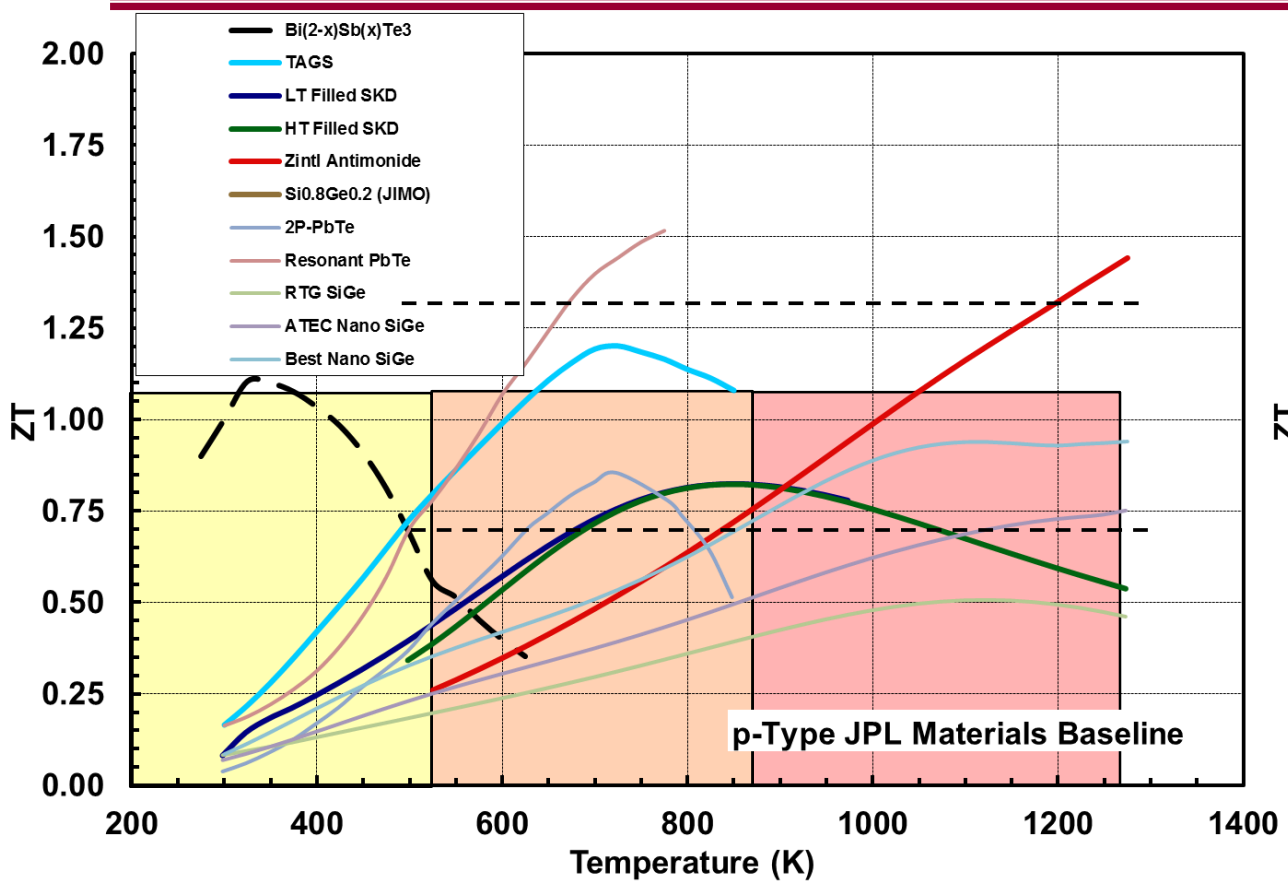
Co-Functional Power/Cooling System

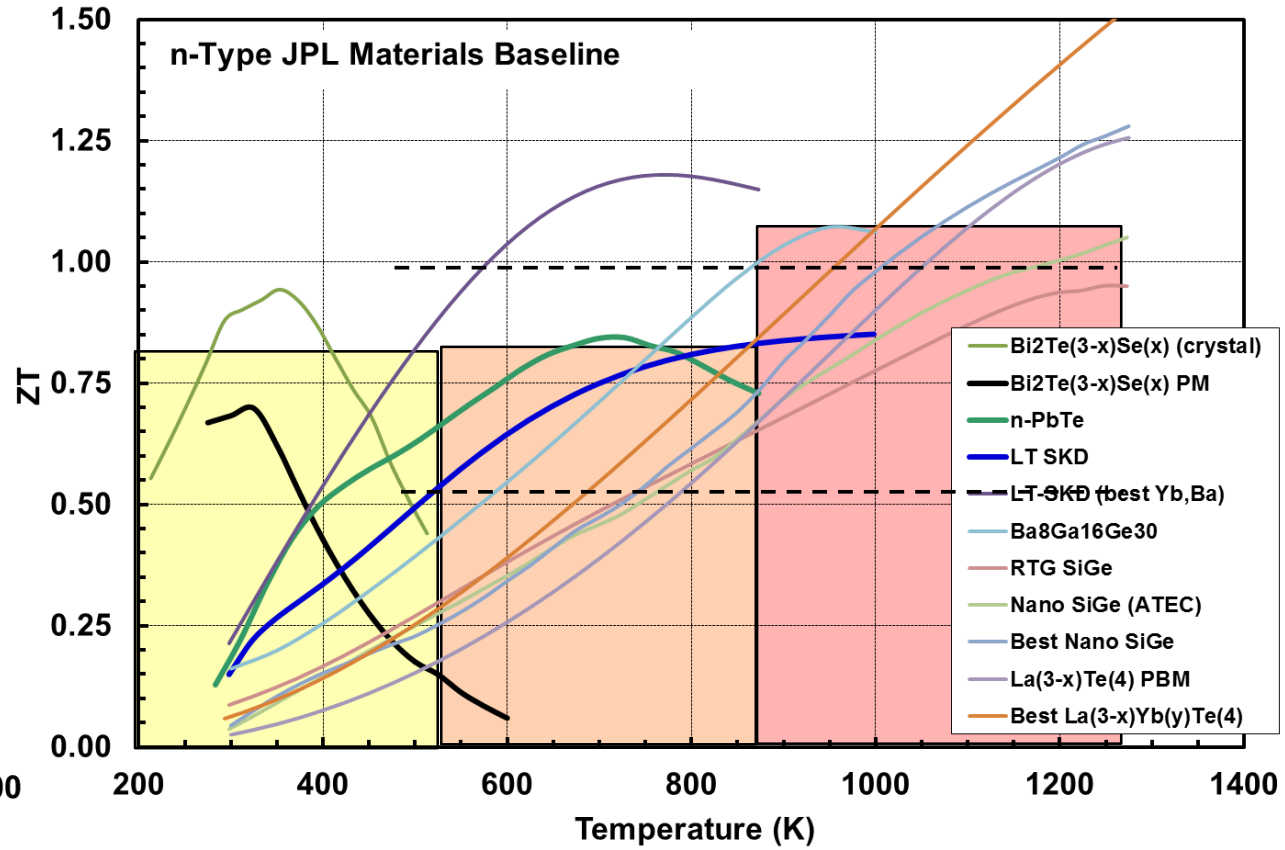


[1] Wang, H., Hendricks, T.J., Krishnan, S., Peterson, R.B., "Experimental Verification of Thermally Activated Power and Cooling System Using Hybrid Thermoelectric, Organic Rankine Cycle and Vapor Compression Cycle", *Proceedings of the 9th Annual International Energy Conversion Engineering Conference*, San Diego, CA, Paper #AIAA 2011-5983, American Institute of Aeronautics and Astronautics, 2011.

[2] Erik W. Miller, Terry J. Hendricks, Hailei Wang, and Richard B. Peterson, "Integrated Dual Cycle Energy Recovery Using Thermoelectric Conversion and an Organic Rankine Bottoming Cycle", *Proc. IMechE, Journal of Power and Energy*, Vol. 225, Part A, 33-43, Professional Engineering Publishing, Ltd., London, 2010.

Advanced High Temperature TE Materials Status





- Best <u>demonstrated</u> couple efficiency of 15% for 1273 K- 473 K using "mature" bulk TE materials; still work to do for demonstrating long life of device/generator technology
- Best segmented couple combination of TE materials <u>predicted</u> to result in ~17% couple--level efficiency for Tcold ~ 473 K (space) and ~ 20% for Tcold of 300 K (terrestrial, water cooled)

All materials made either in house or leveraged through collaborations

Multiple Extended Range/Multi-Purpose Aircraft Applications

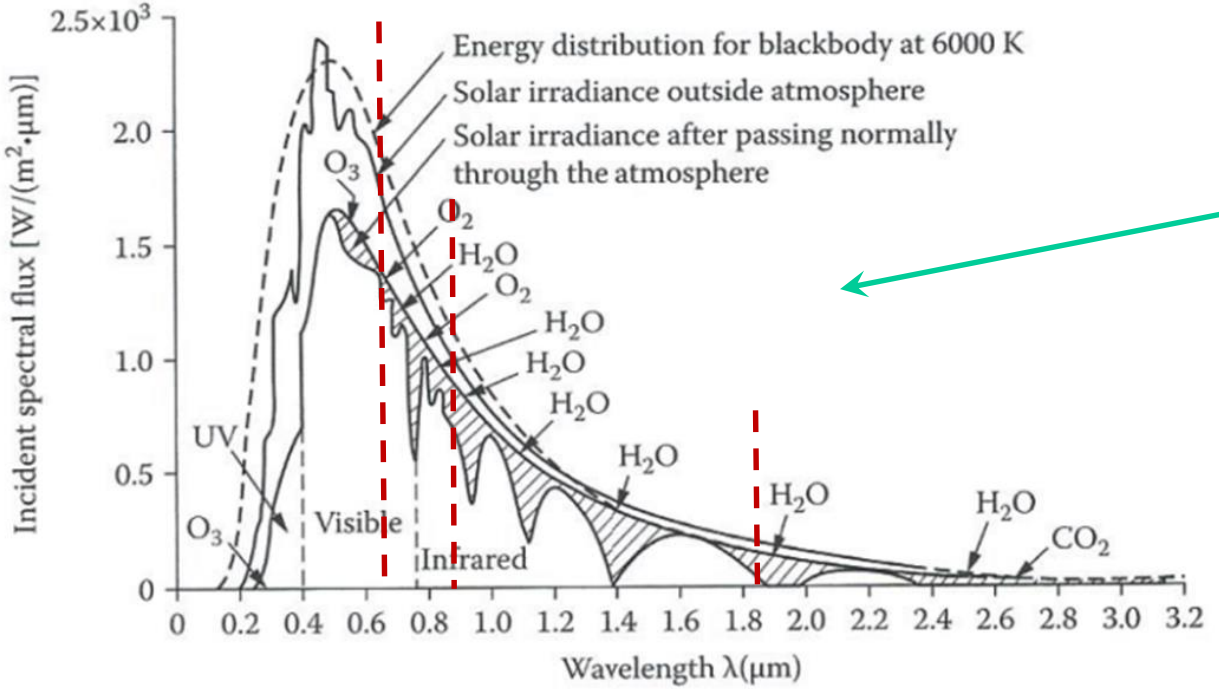
- Gray Eagle
- Predator-B Reaper
- Predator-C Avenger

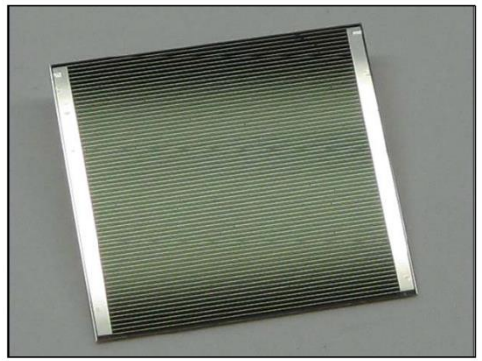
http://www.ga.com/unmanned-aircraft-systems-and-sensors

- 125 kW of Fuel Energy in Predator Gray Eagle
  - 25% → Aircraft Thrust
  - 75% → Everywhere Else Including Waste Heat in Engine
- Currently No Waste Energy Recovery Used on ER/MP Aircraft

Hybrid Photovoltaic / Thermal Cycle Power Cycles

- Most Recent Emerging Terrestrial Applications of Advanced Solar PV Cells
  - Grid-Level PV Solar Power – Airports, Carports, Government Buildings, Solar Farms (Spain & California)
  - Residential and Commercial Buildings – Flat Roofs, Sloped Roofs, Industrial Roofs
  - Flexible Constructions – DSSC for Low Intensity Harvesting Supporting Building Energy Management





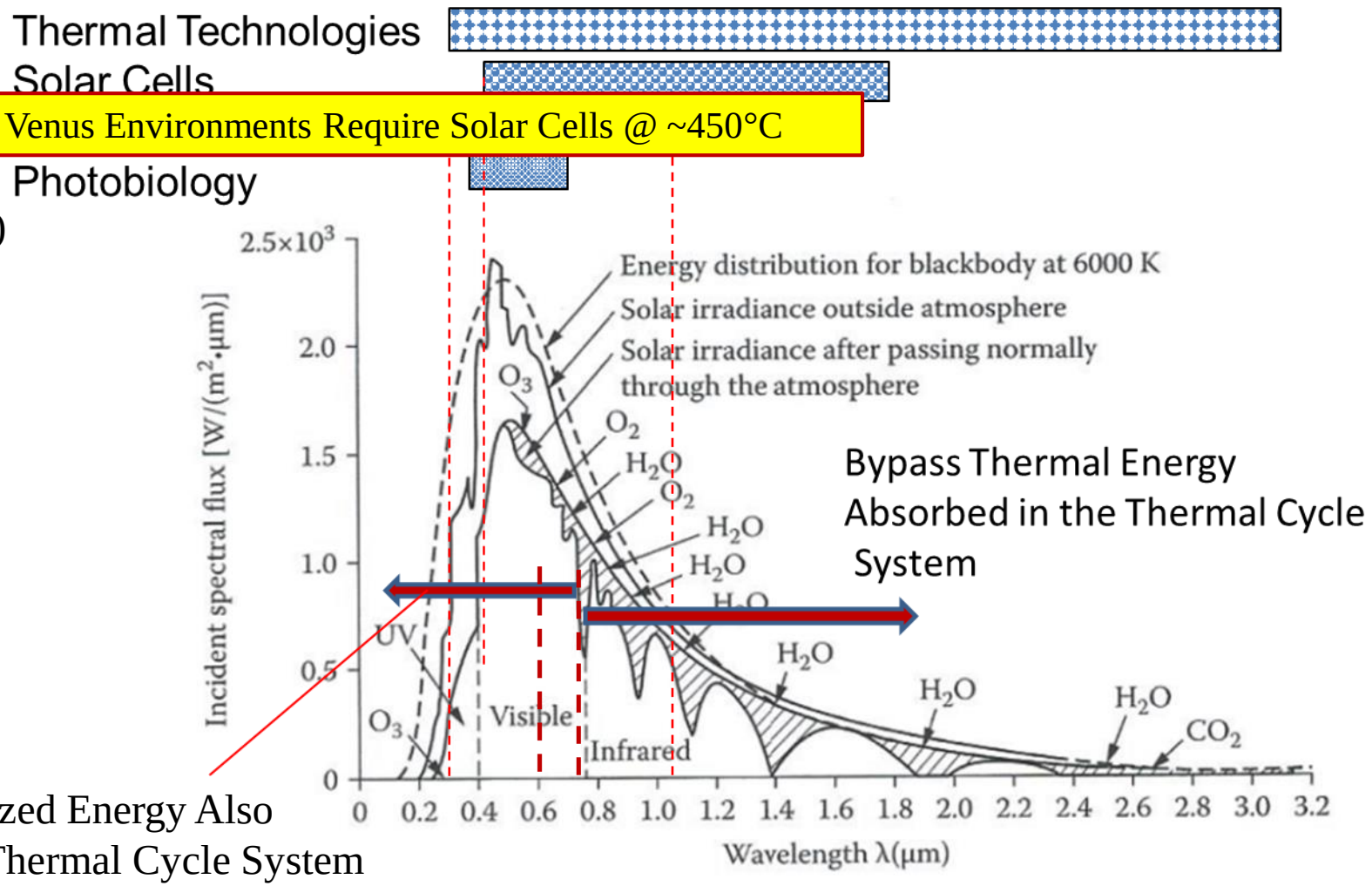
- 39.2% Efficient Multi-Junction (MJ) PV Cell
- Triple Junction PV Solar Cell
- GaInP (1.88 eV) / GaInAs (1.41 eV) / Ge (0.67 eV)
- Advertised to Operate Up to 110°C

	Wavelength Range	Spectrum	Energy Content
Photovoltaic	200 - 1100 nm	UltraViolet & Visible	79.6%
Thermal Thermoelectric	1100 nm - 6000 nm	Infrared	20.1%

- Energy Recovery Opportunity
  - Solar PV Cells Do Not Capture Everything
  - Higher Wavelengths Have Significant Energy Content

Full-Spectrum Solar / Thermal Cycle Power 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)



❖ NASA Overlap: Venus Environments Require Solar Cells @ ~450°C

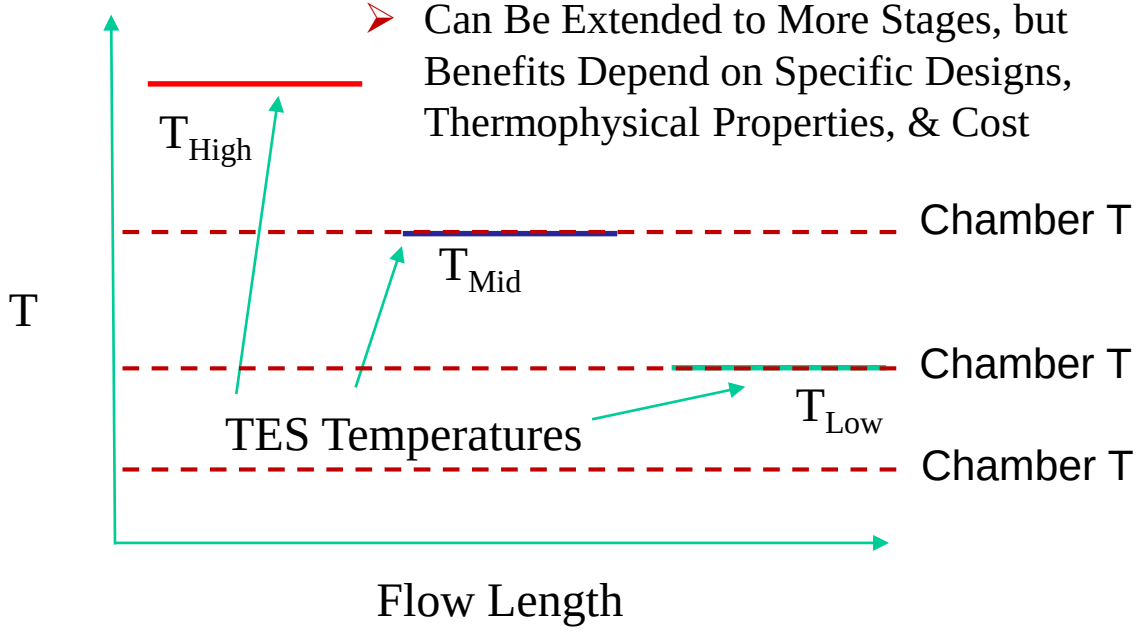
- **Technical Challenges**
  - High Temperature PV cells (~400°C)
  - Compact Stirling cycles, Brayton cycles, Organic Rankine cycles
  - Wavelength splitting (efficiency)
  - Thermal interfaces
  - High-Temperature thermal energy storage (<$15/kW$_{th}$)
  - Cost
    - LCOE ~ $0.06/kWhr is high bar

Cell Thermalized Energy Also Absorbed in Thermal Cycle System

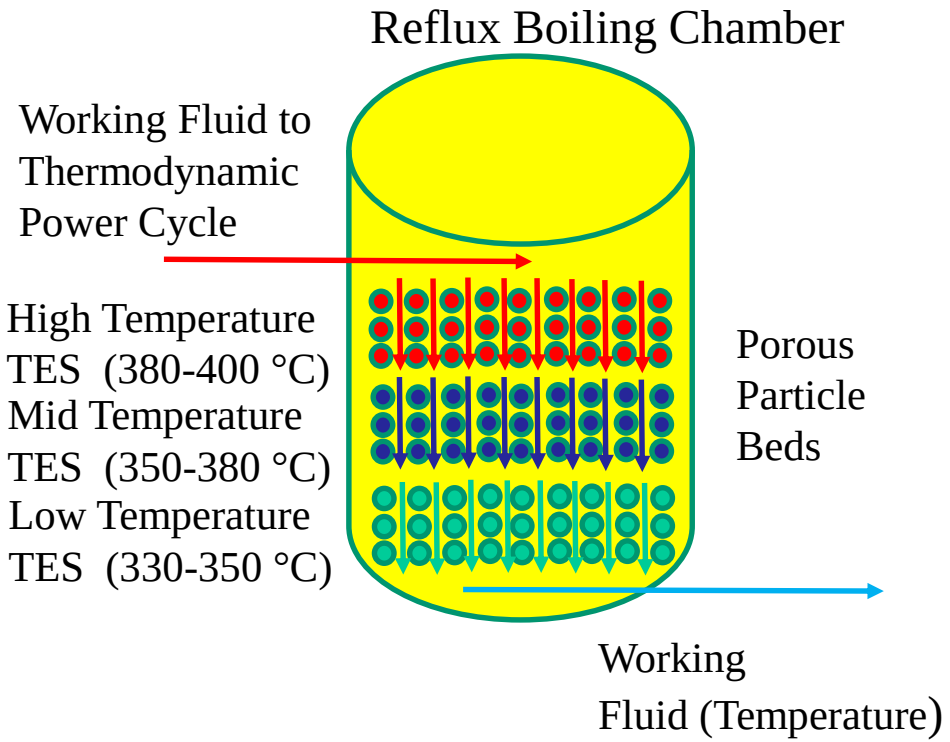
Multiple TES Materials

- 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

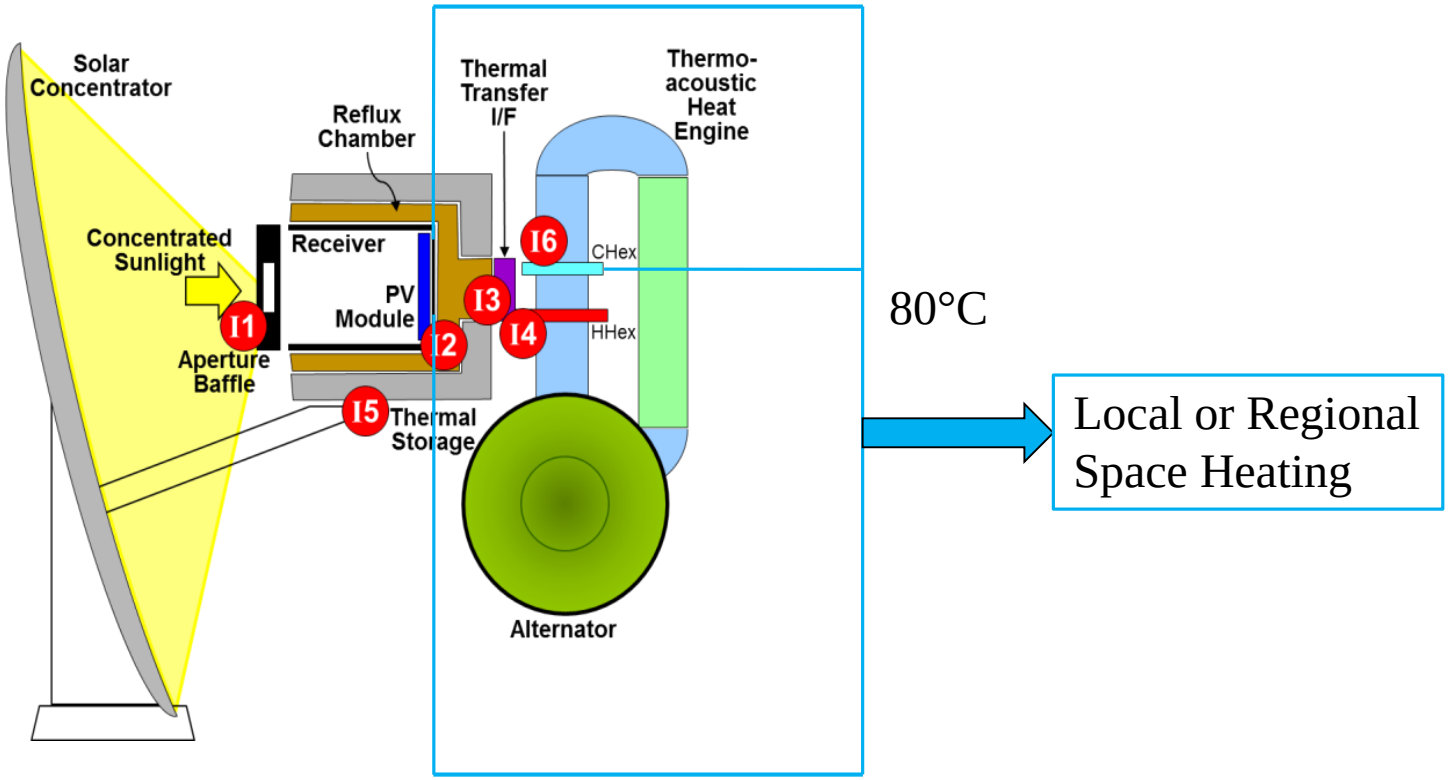


TES Charge Process



Full Spectrum Solar/Thermal Engine/Space Heating System

- Systems Can Be Conceptualized to Increase the Energy Management Efficiency
  - Use All the Energy At Its Appropriate Level
  - Energy Storage Built-In
- New Approach to City-Wide or Region-Wide Energy Sustainability & Efficiency
  - Single Building
  - City Block
  - City Wide
- Other Energy Sources (Natural Gas) Could Be Accommodated and Integrated Within This Approach



NASA Overlap: Potential Mars/Moon Habitat Power

David E. Lee, Bill Nesmith, Terry Hendricks, Juan Cepeda-Rizo, Michael Petach, Emanuel Tward, Cecillia Penera, John Pohner, Scott Whitney, Jonathan Grandidier, "Efficient Heat Transfer Methods in a Hybrid Solar Thermal Power System for the FSPOT-X Project", *Proceedings of the ASME 2015 Power and Energy Conversion Conference (PowerEnergy2015)*, Paper #PowerEnergy2015-49658, San Diego, CA, July 2015.

Final Thoughts & Conclusions

- NASA/National Defense Power System Development Provides Direct Technology Pathway to Terrestrial "Energy Harvesting & Recovery" Power Systems
- Maybe a 10-20 Year Lag – Getting Shorter Every Year
- Terrestrial Power Has Many Similar Requirements as Spacecraft Systems
  - Cost is Always An Issue
  - Space Environments More Extreme Than Terrestrial (Hot - Venus & Cold – Mars & Beyond)
  - Terrestrial Applications Have Severe Cost & Environmental Requirements
    - Spacecraft Power System Materials in Large Quantities in Earth-Based Applications Can Sometimes Cause Severe Issues on Earth
    - System Costs Generally Need to approach $1-3/W to be Competitive – TE Power System Costs are Often Heat Exchanger Driven
    - Robust, Low Cost TE Couples and Module Devices Required to Enable New TE System Applications
    - Hybrid Solar Power Concepts Extend Our Sustainable Options
- 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

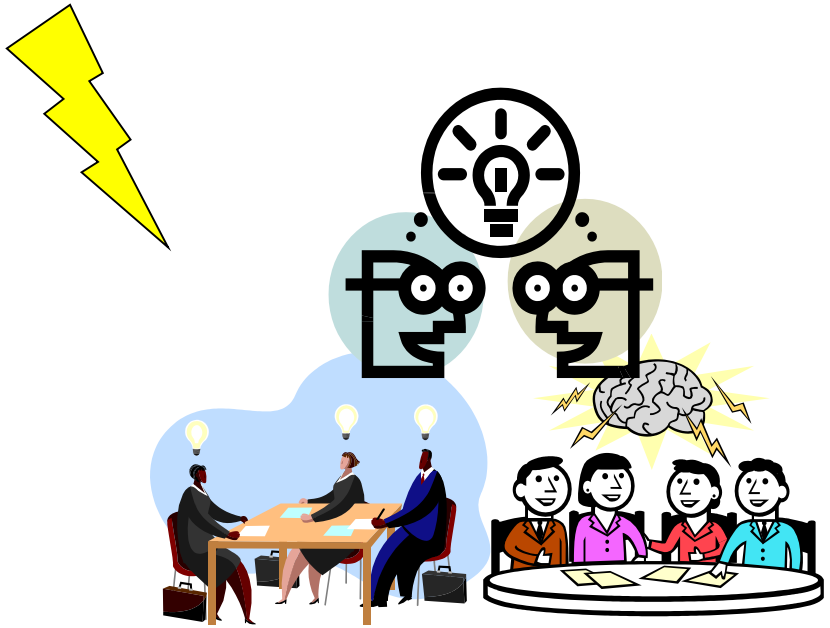
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

Thank you for your interest and attention

We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

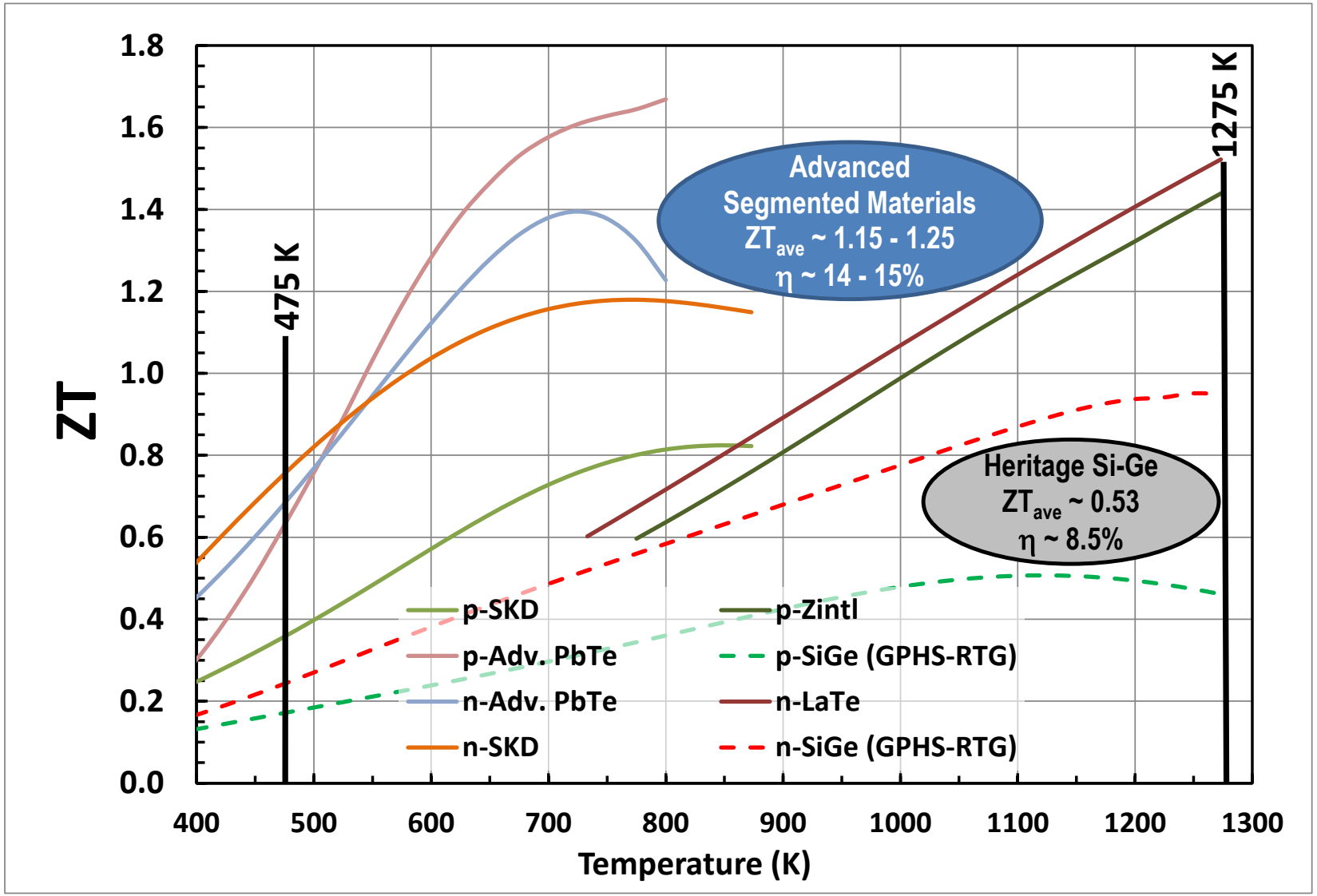
Questions & Discussion



BACKUP SLIDES

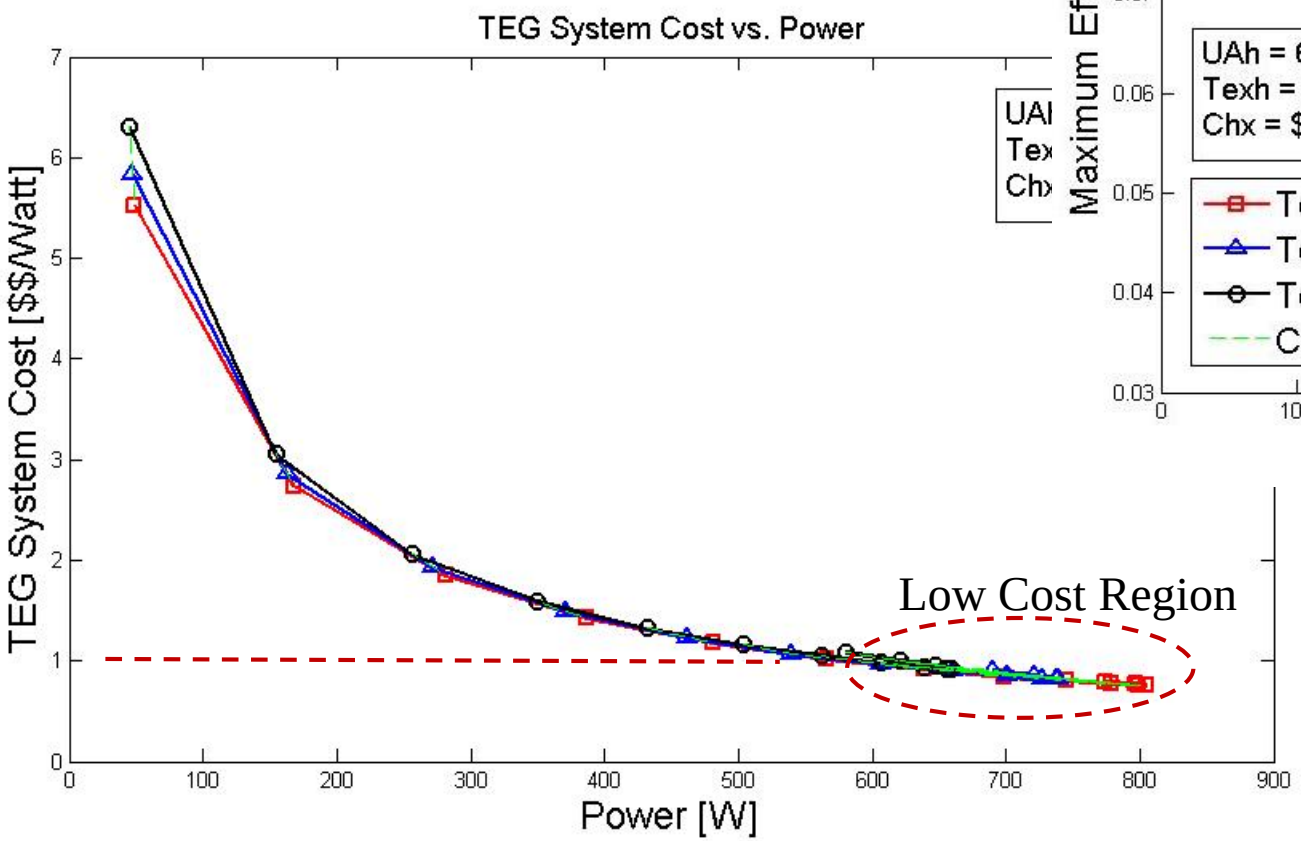
New Generation of "Mature" Advanced TE Materials

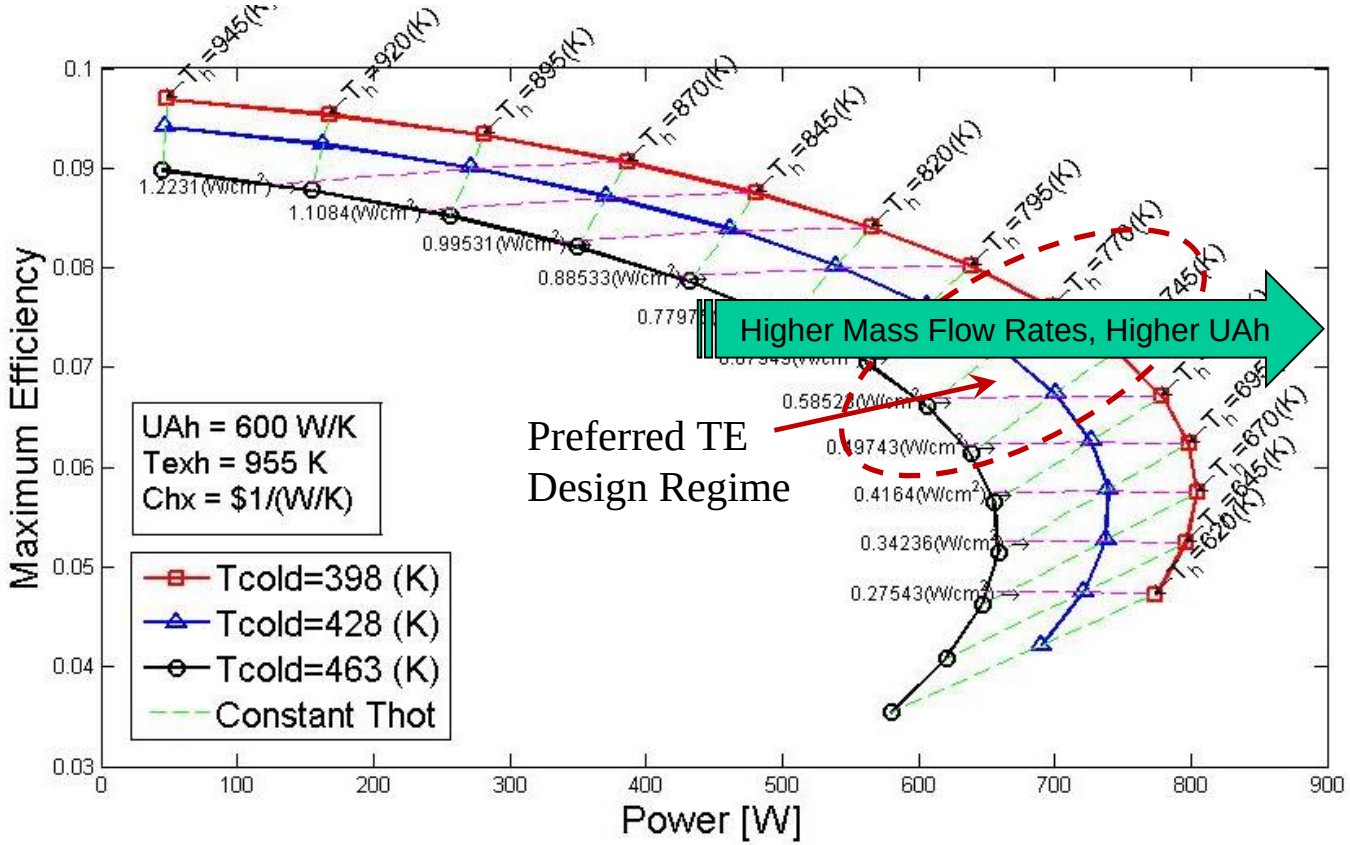
Large performance gains over heritage PbTe & Si-Ge alloys



Results – T_{exh} = 955 K, Heat Exchanger Costs $1/(W/K)

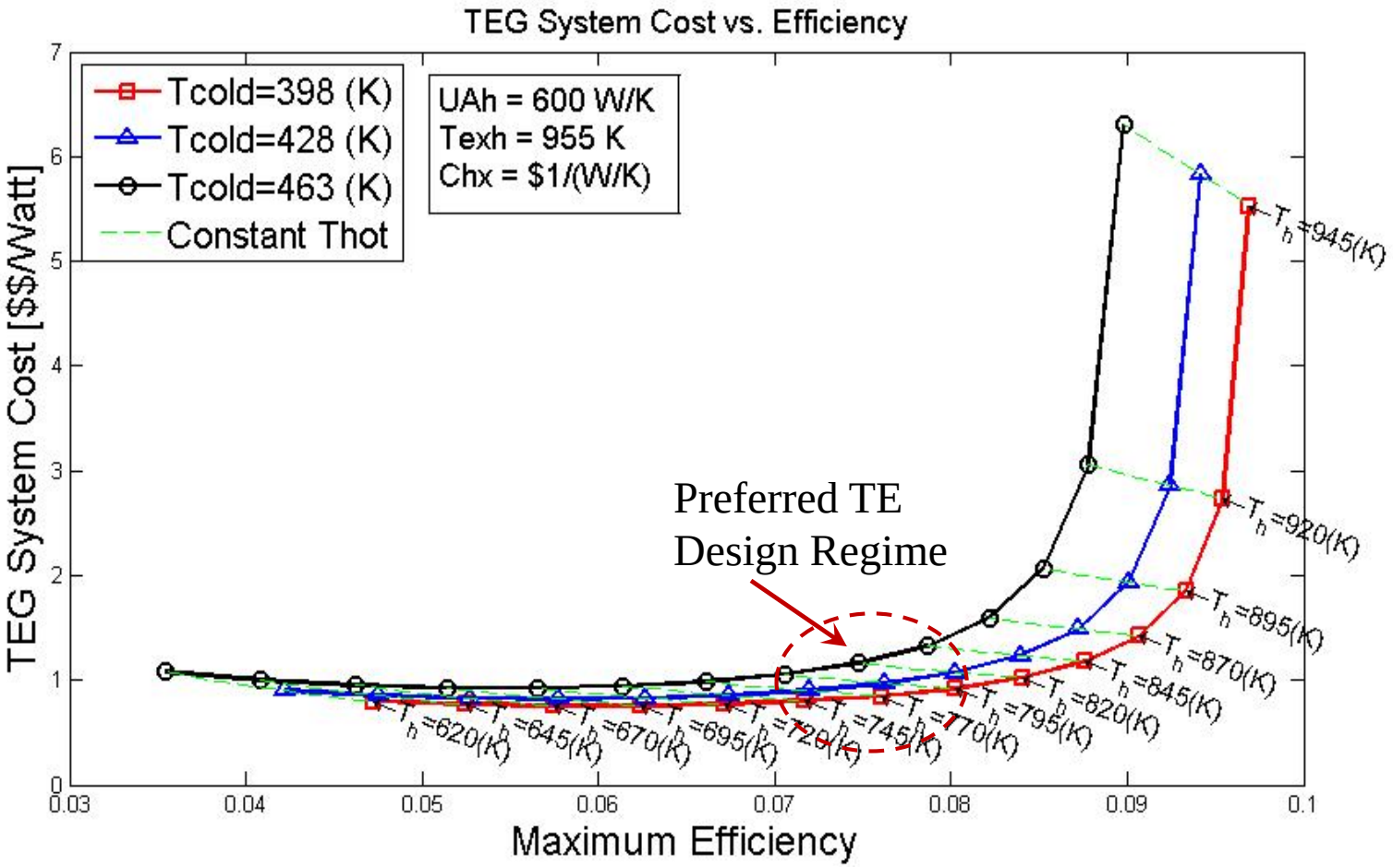
- Preferred TE Design Regime Identified
  - Cost Dependence on Power, T_{cold} , T_{hot} Shown Below
- Low Cost Regions Identified
  - Coincides With Preferred TE Design Regime





- Cost-per-Watt Asymptotically Approaches Low Cost Regions (Basically ∝1/P When Heat Exchangers Dominate)
- Approaches Point of Diminishing Returns

Results – T_{exh} = 955 K, Heat Exchanger Costs $1/(W/K)

- TE Designs Can Approach $1/W Only When Heat Exchanger Costs Approach $1/(W/K) and One is in Preferred TE Design Regime
- Preferred TE Design Regimes Allow us to Move into Higher Efficiency, Higher Power Densities and Fluxes With Very Little Cost and Power Penalties – "PRETE (Pretty)" Design Regime
  - We Can Win
  - If and only if Heat Exchanger Costs Are Low Enough
- Point of Diminishing Returns Evident Here Also

Heat Exchangers Dominate The Costs, Even at Low Cost Levels and It is Extremely Difficult to Escape this Regime