The Jet Propulsion Laboratory's Thermal Energy Conversion Technologies Groups

Reliable Thermal-to-Electric Energy Conversion Technologies

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Thermal Energy Conversion Groups

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Pasadena, California, USA

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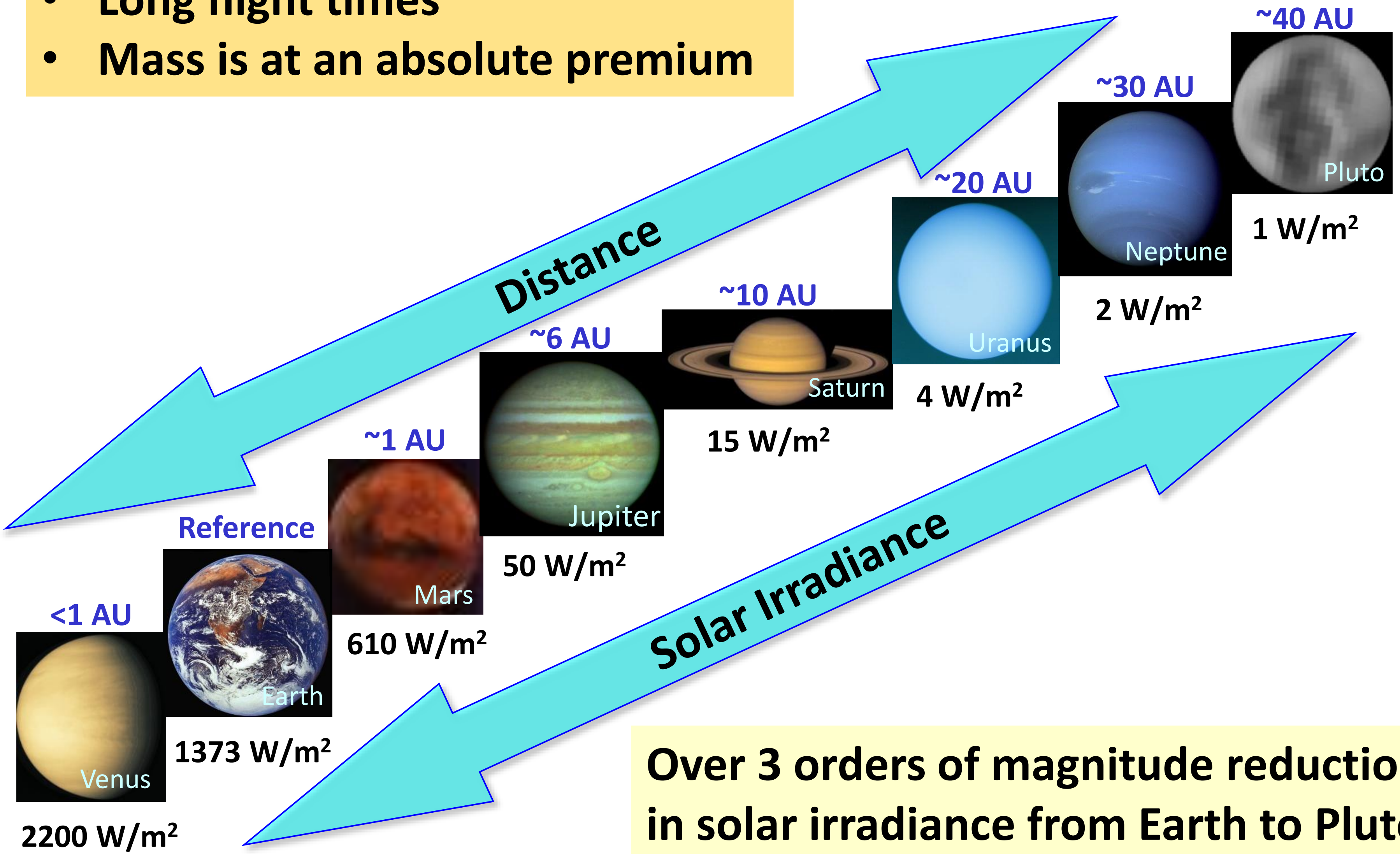
Major Power Challenges of Solar System Missions

- **Long flight times**
- **Mass is at an absolute premium**

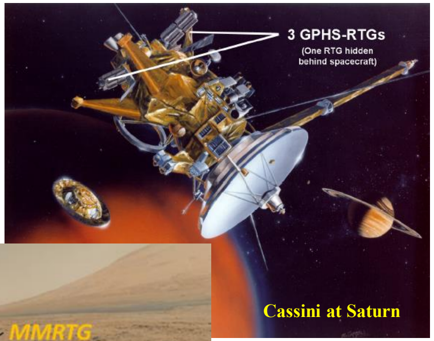


Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto

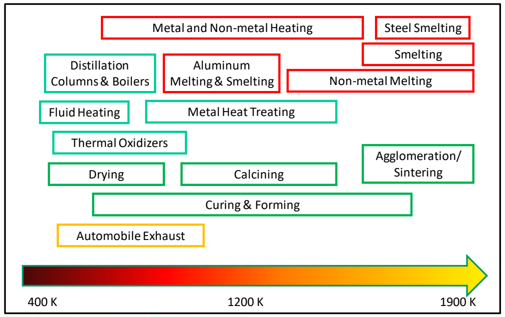
Breadth of Thermoelectric (TE) Applications

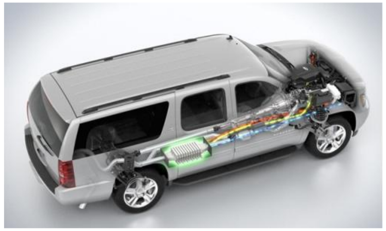
Power, Cooling, Sensing

Ultra-Reliable (30+ Years), Modular, Scalable

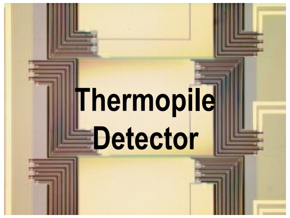


50 years of NASA Investment in High Temperature TE Power Generation Technology for Deep Space Science Exploration



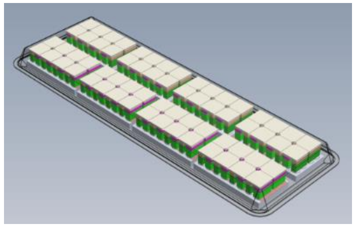


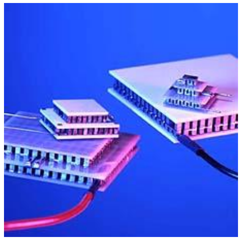
Waste Heat Recovery & Energy Harvesting



IR Sensing

All-Solid-State Refrigeration

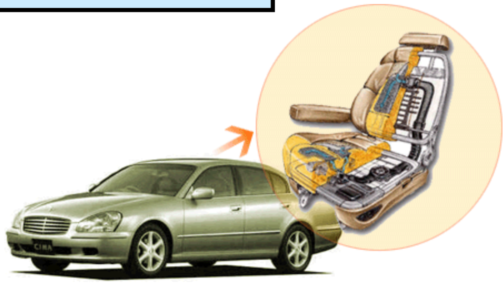




Autonomous Remote Power Generator

TE Converter

A Key Enabling Technology Component

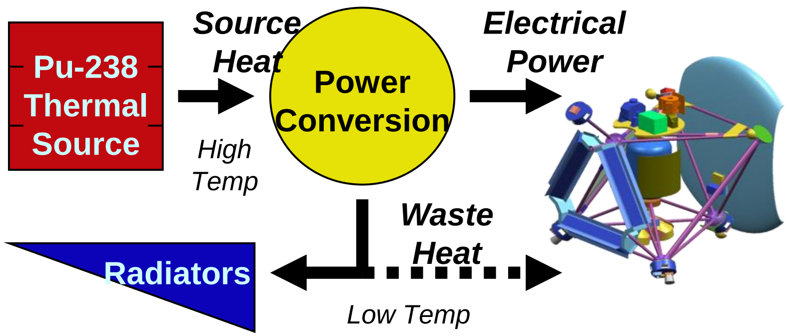


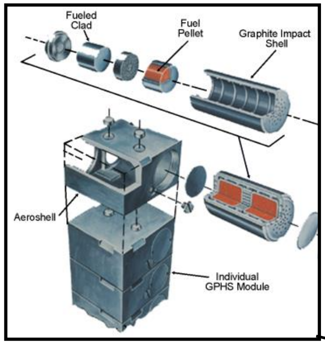
Active heated & cooled seating system

TE at JPL

RTG Technology - What is an RTG?

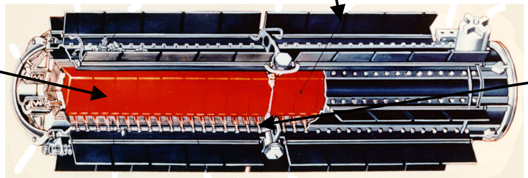
RTG is a thermoelectric conversion system that converts heat produced from natural alpha (α) particle decay of plutonium into electrical energy (DC)

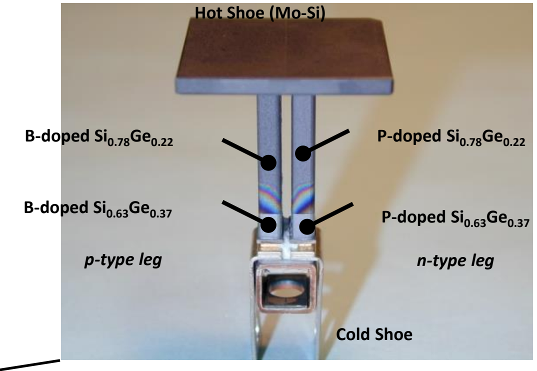




Heat Source Assembly
(GPHS Modules)

Housing & Radiator Assembly





Thermoelectric couple (572 couples used in the GPHS-RTG)

GPHS-Radioisotope Thermoelectric Generator (RTG)

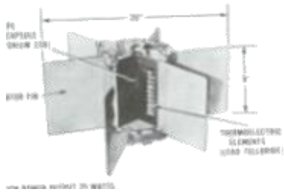
RTG Technology- Key Performance Characteristics and Benefits

- Performance characteristics
  - Specific power (W/kg) -> Direct impact on science payload
  - T/E efficiency -> Reduce PuO_2 needs
  - Power output
- Benefits
  - Highly reliable with a high level of redundancy
    - Hundreds of discrete converters in series/parallel configuration
  - Proven long-life operation
    - Both Si-Ge and PbTe-based RTGs have demonstrated more than 30 years of operation
    - Well known converter aging mechanisms (all solid-state)
    - Failure mechanisms well understood
  - Proven operation in extreme environments
    - Radiation resistant
  - High grade waste heat available for spacecraft thermal management
  - Friendly to science instruments
    - Produces no noise, vibration, or torque during operation
    - No electromagnetic interference
  - Long life capability
    - Most outer planet missions > 10 years
    - Missions often get extended

RTG Technology - Missions

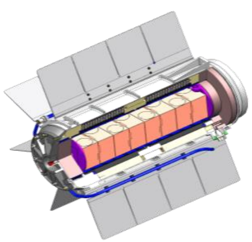
PbTe-based

SNAP-19



40 W_e, 3 W/kg
6.3% Efficiency
Deep space and planetary surface operation
➢30 Year life demonstrated

MMRTG



120 W_e, 2.8 W/kg
6.3% Efficiency
Deep space and planetary surface operation

Mission	RTG	TE	Destination	Launch Year	Mission Length
Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15
Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9
Apollo 12	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8
Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	31
Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15
Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35
LES 8	MHW-RTG (4)	Si-Ge	Earth Orbit	1976	16+
LES 9	MHW-RTG (4)	Si-Ge	Earth Orbit	1976	16+
Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	39+
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	39+
Galileo	GPHS-RTG (2) RHU(120)	Si-Ge	Outer Planets	1989	14
Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	19
Cassini	GPHS-RTG (3) RHU(117)	Si-Ge	Outer Planets	1997	19+
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	11+
MSL	MMRTG (1)	PbTe	Mars Surface	2011	5+

SiGe-based

MHW-RTG

158 W_e, 4.2 W/kg
6.5% Efficiency
Deep space operation
➢30 Year life demonstrated

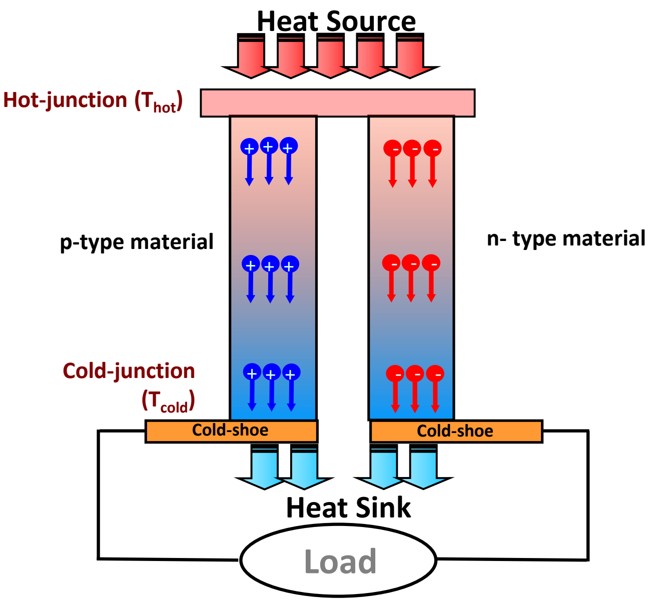
GPHS-RTG

285 W_e, 5.1 W/kg
6.5% Efficiency
Deep space operation
> 18 Year life demonstrated

RTGs have been successfully used on a number of long-life missions

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

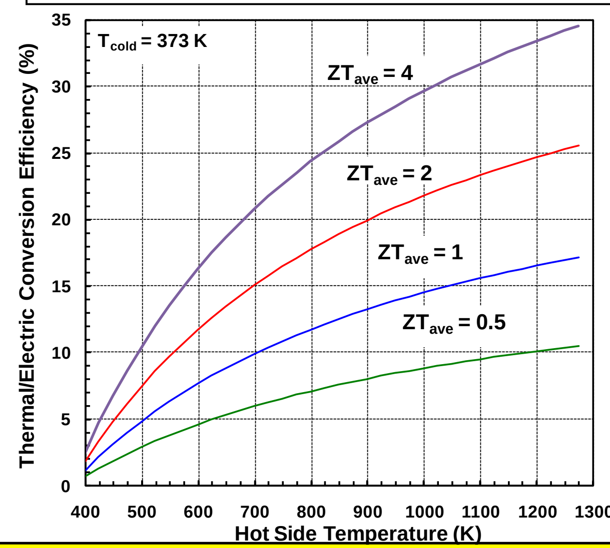
$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

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

Carnot | TE Materials

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

Conversion Efficiency



Power generation

(across 1275 to 300 K)

State-Of-Practice materials:

$ZT_{average}$ ~ 0.5

State-Of-the-Art materials:

$ZT_{average}$ ~ 1.1

Best SOA materials:

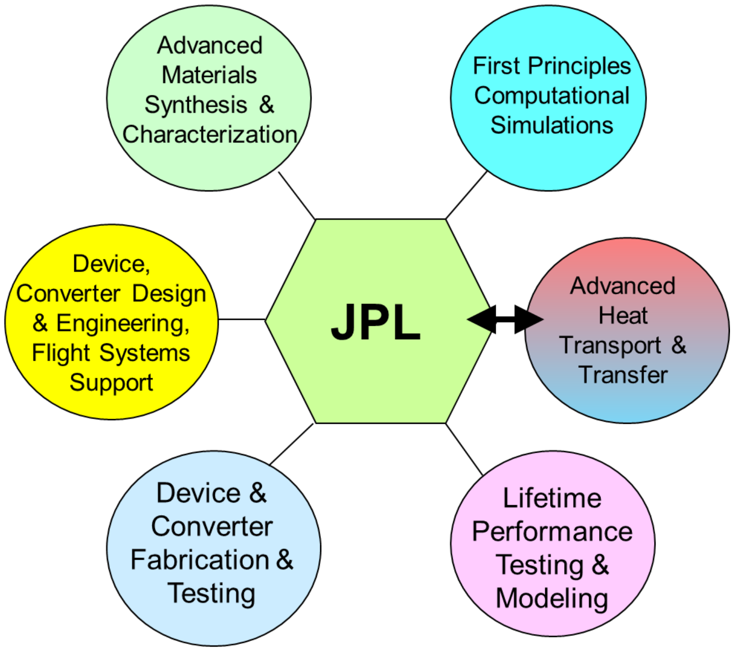
ZT_{peak} ~ 1.5 to 2.0

Conversion efficiency is a direct function of ZT and ΔT

Expertise in Thermal-to-Electric Energy Conversion Technologies and Systems

World-Class Recognized Technical Leadership in Solid-State Thermal-to-Electric Energy Conversion

Effective Collaborations with Thermal & Structural JPL Groups



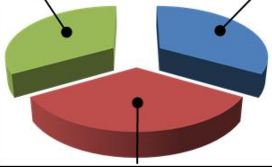
Unique set of capabilities
- Recognized world leadership for high temperature TE materials & devices
- Extensive expertise in developing and testing designs for long life applications in extreme environments
- Robust collaborations with academia and industry
- TECT Group staff ~ 28 PhDs, engineers and laboratory technicians

Also involved in other energy conversion and advanced materials technologies
- Direct energy conversion (alpha- and beta-voltaics)
- Solar-thermal
- Hybrid power generation/energy storage
- Dynamic engines
- Aerogel
- Materials for energy-related applications

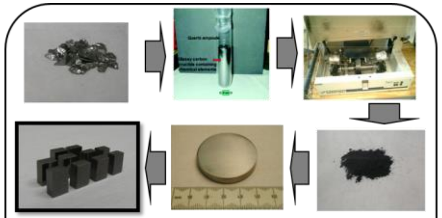
Collaborating and Partnering

U.S. National Laboratories
- NASA
- Department of Energy
- Department of Defense

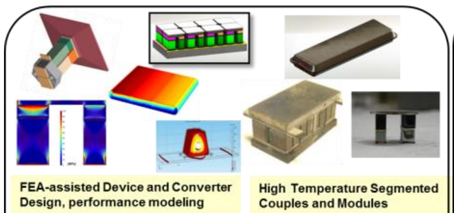
Universities
- U.S. Universities
- International collaborators



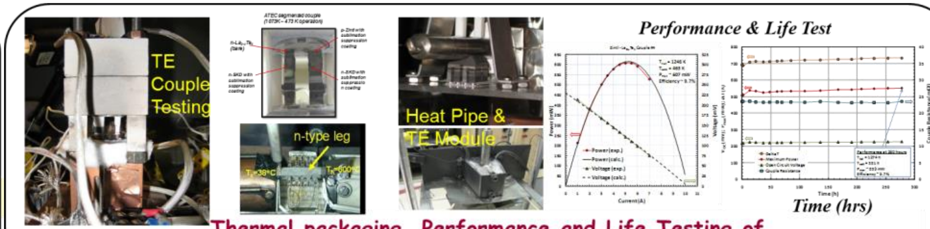
Industry
- Aerospace technology and systems
- Vehicle & transportation industry
- Oil and gas exploration industry
- Startups and spinoffs in the waste heat recovery and renewable energy fields



Scale-up of Powder metallurgy of Advanced TE materials & components



Design, Modeling, Fabrication & Assembly of New TE Power Generation Devices



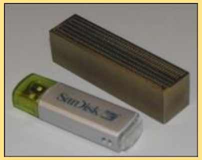
Thermal packaging, Performance and Life Testing of High Temperature, High Performance Thermoelectric Power Generation Devices

JPL Technologies for Terrestrial Energy Recovery

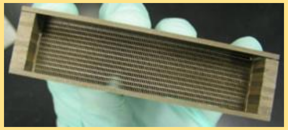
- **System Solutions Needed to Recover Energy Throughout the Terrestrial Energy Complex**
  - Goal: Produce Power & Residential / Commercial Space Heating
  - Radiant Collectors, Rankine cycles, Stirling cycles, Advanced Heat Exchangers & Thermoelectric Conversion
  - High-Temperature TE & Structural Materials and Systems; High Temperature Thermal Energy Storage; Two-Phase Flow Systems

- **Various Industrial Processes**
  - Steel, Glass Furnaces, Aluminum Processes, Petro-chemical all have common requirements
  - Process Temperatures Available: 760 – 1400°C
  - Very High Energy Flows ~ 10 Megawatts in Many Cases
  - High-Temperature, Energy Recovery Heat Exchanger/TE/Rankine Cycle Systems
  - Large International Interest in WHR Systems

www.dpp-Europe.com



SERDP, 2010



Advanced Heat Exchangers

- **High-Temperature Aircraft Energy Recovery**
  - 670+°C Energy Recovery Environments
  - 500-2000 W Systems
  - Examples: Engines, Exhaust Streams

- **Hybrid Concentrated Solar PV/Thermodynamic Cycle Wavelength-Splitting Systems to Achieve High Exergy Efficiency - Commercial Concentrated Solar Power Systems**
  - 10's kW to Megawatts of Power
  - Thermal/Power System Applications @ 400-800°C

- JPL has a long history of contributions to NASA's RPS-powered space science and exploration missions
- JPL has unique capabilities and has developed advanced technologies in high temperature thermoelectric power generation technologies in support of NASA's RPS program
- These technologies could be applied to some terrestrial applications (auxiliary power systems and waste heat recovery)

Example Near-Term Potential Technology Areas of Cooperation Between MHI and JPL

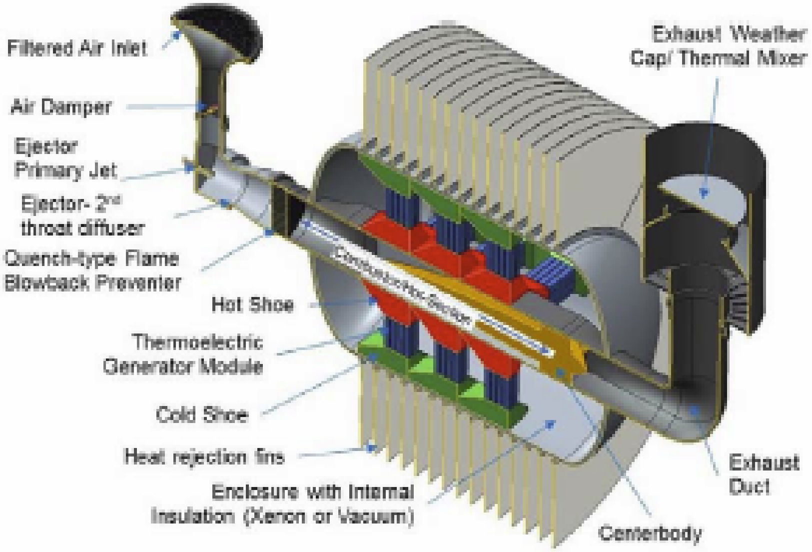
MMTEG Project Summary

GTI, in partnership with Jet Propulsion Laboratory (JPL), will develop a high efficiency, Methane Mitigation Thermoelectric Generator (MMTEG) prototype for oil and gas field applications.

Schedule: <18 months
Cost: ~$1.55M (includes $1.2M DOE funding)
DOE Grant: DE-FE0029060

Specific objectives are:

- Design & fabricate a prototype 12We system
- > 7% system efficiency
- Peak TE module efficiency >9% (600C basis)
- Low-NOx burner
- High Reliability for the MMTEG subsystem
- Projected GHG reduction of >1000:1 (long-term)
- Low cost target per 12We system (providing instrument air for an entire well pad)



Notional Design Concept

A low-cost, reliable instrument air system for pneumatic valve actuation will provide payback within ~20 months. Over 100,000 gas well pads can utilize this simple retrofit.

FSPOT-X Demonstration

Demonstrate an integrated hybrid solar thermal power system

- Power system integrates
  - concentrated solar photovoltaic (CPV) cells
  - thermoacoustic power converter (TAPC)
  - thermal energy storage (TES)
- System produces electricity from sunlight directed at the power system by a solar concentrator
- By combining CPV, TAPC and TS, the FSPOT-X power system efficiently converts photons to electrons through effective heat transfer methods
- Demonstration of integrated PV/TAPC/TES power system to measure end-to-end efficiency and quantifying exergy performance

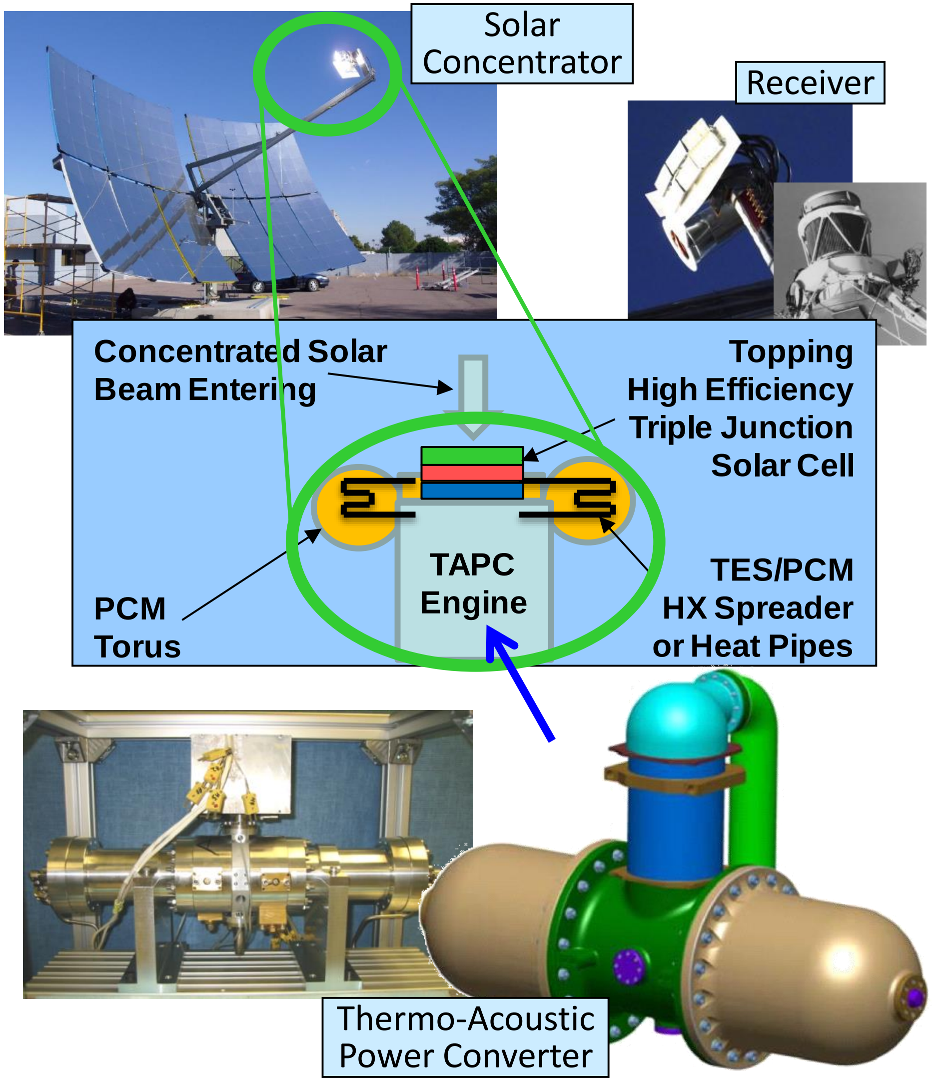
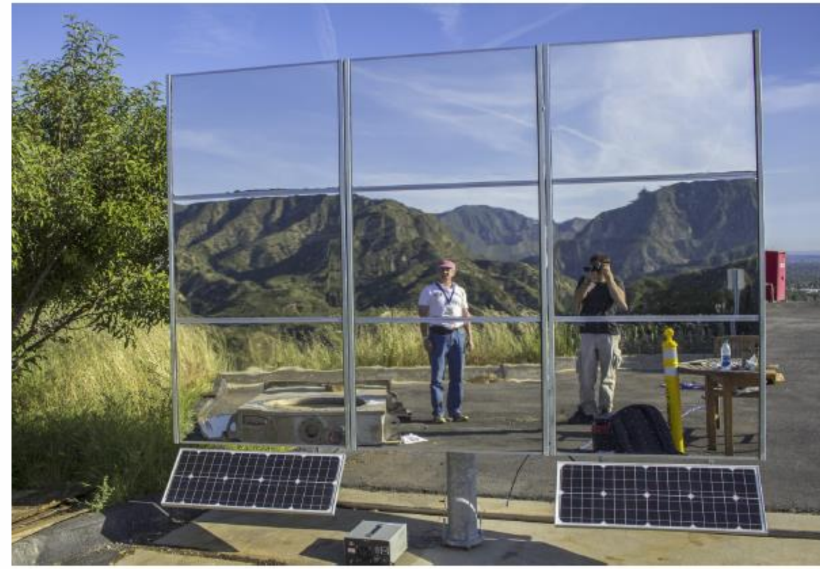


Figure 32: JPL heliostat prototype after mechanical assembly was completed.



Heliostat on Mesa

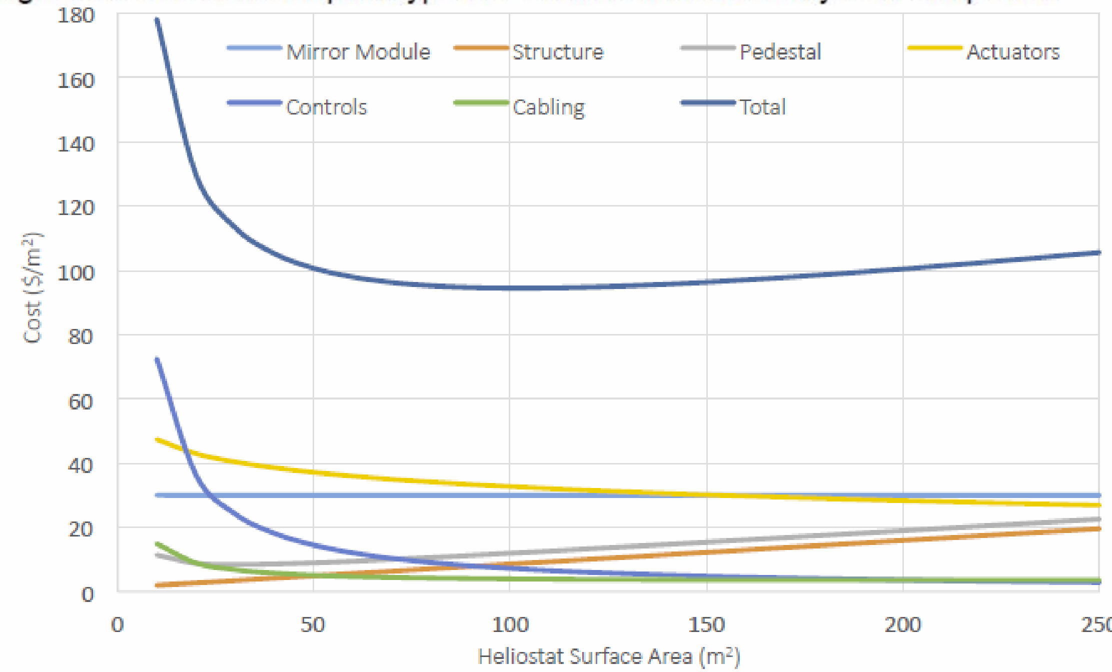
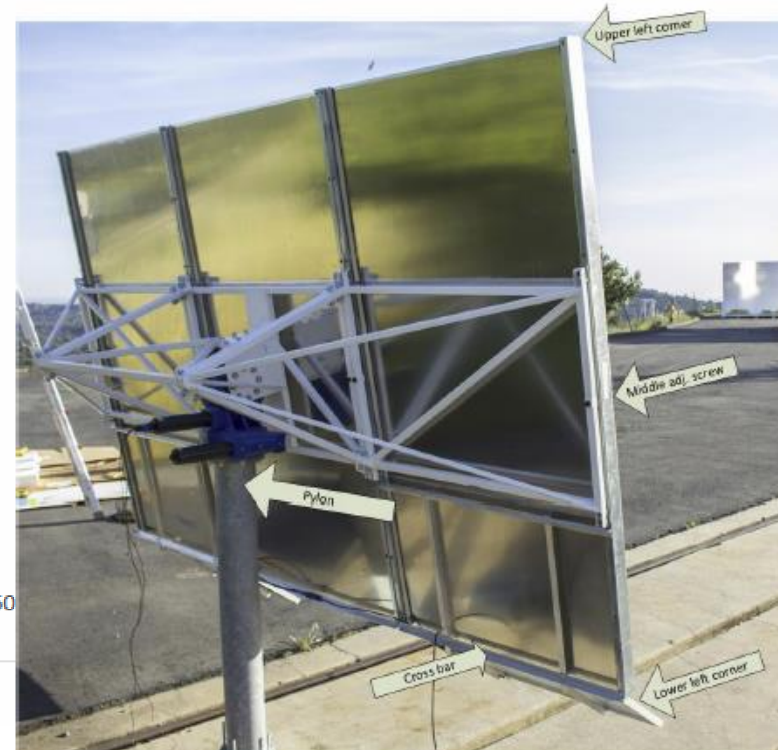


Figure 36. Heliostat cost trade as function of size



TE at JPL