Thermoelectrics: from Space to Terrestrial Applications – Successes, Challenges and Prospects

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Mars 2013

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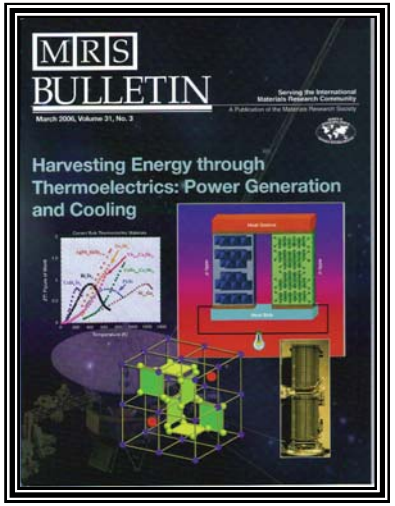
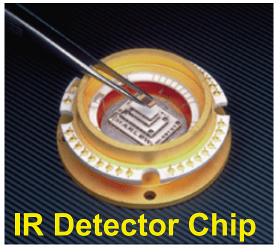
Thermoelectric (TE) Applications
Power, Cooling, Sensing

Cassini - Saturn - NASA

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

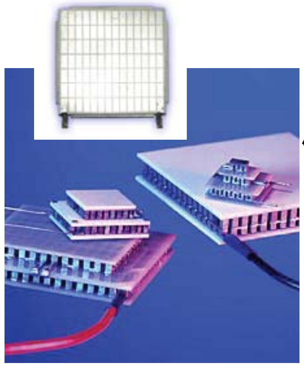

MRS BULLETIN
Harvesting Energy through Thermoelectrics: Power Generation and Cooling



IR Sensing

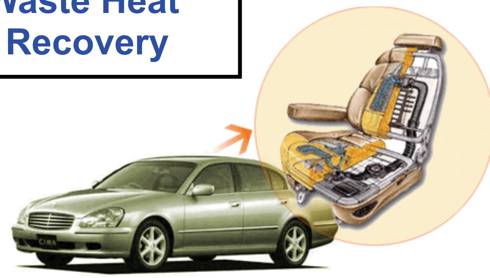
All-Solid-State Refrigeration

Waste Heat Recovery



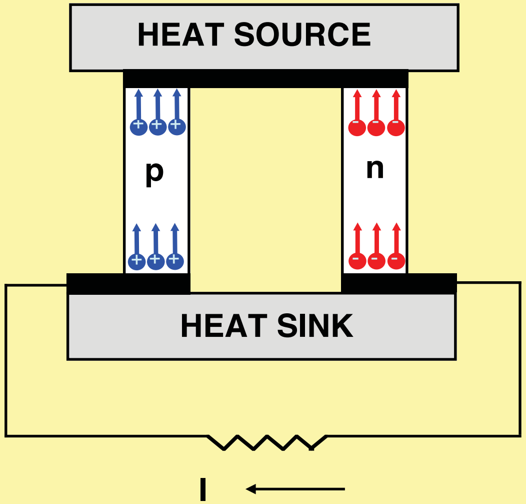
TE Power Module
A Key Enabling Technology Component

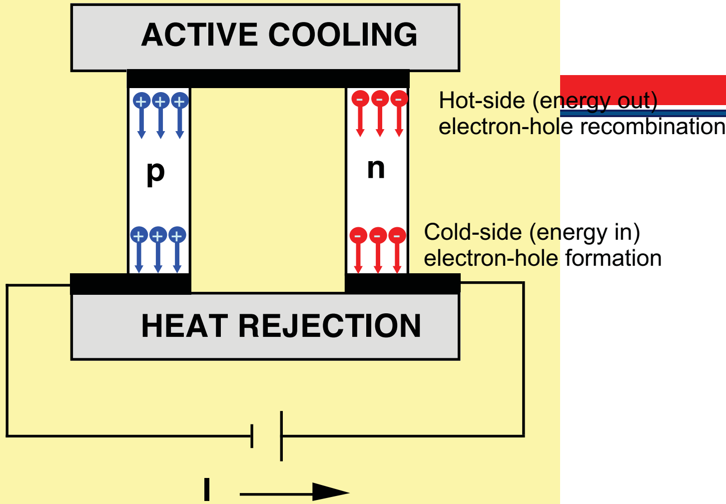
Autonomous Remote Power Generator



Active heated and cooled seating system

THERMOELECTRIC BASICS





Power generation (Seebeck effect)

Refrigeration (Peltier effect)

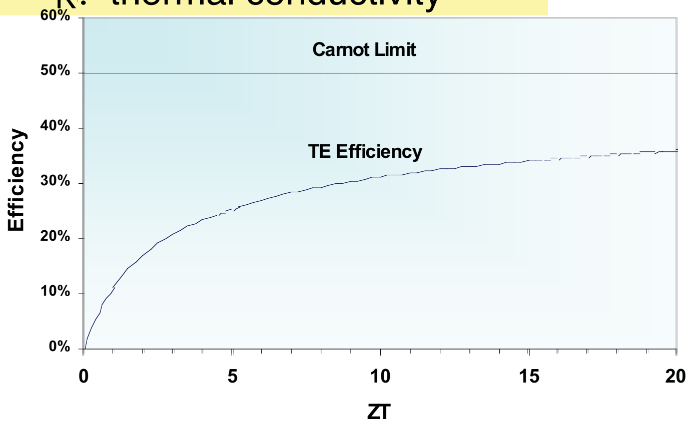
Efficiency: $\eta = \frac{(T_H - T_C)\ (\gamma - 1)}{(T_C + \gamma T_H)}$

$C.O.P. = \frac{(\gamma T_C - T_H)}{[(T_H - T_C + (1+\gamma)]}$

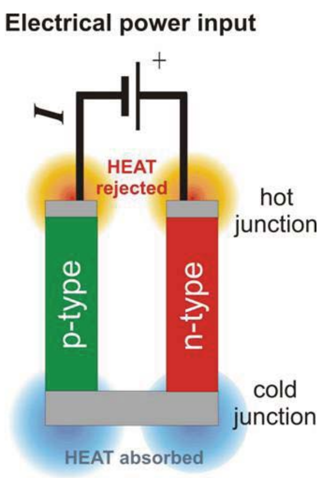
With: $\gamma = (1+ZT)^{1/2}$ $Z = \frac{\alpha^2}{\rho \kappa}$

α: Seebeck coefficient
ρ: electrical resistivity
κ: thermal conductivity

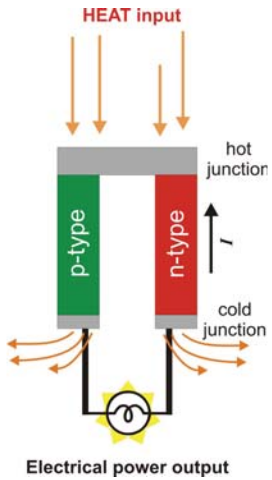
- Large Z values are needed to achieve high conversion efficiency or coefficient of performance (COP)
- Thermoelectrics is all solid-state



Simple Thermoelectric Devices

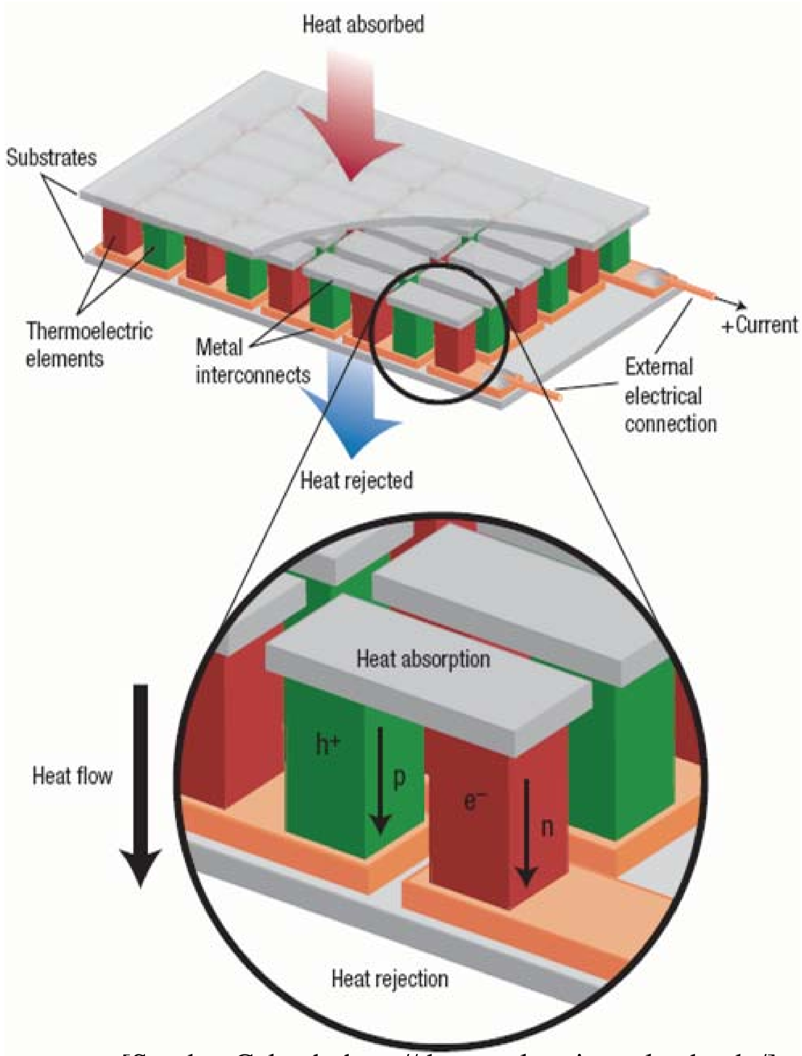


Cooler Mode Thermocouple



Power Generation Thermocouple

- ‘Close Packed’ modules easier to handle, lower losses than individual thermocouples



[Snyder, Caltech, http://thermoelectrics.caltech.edu/]

Selection Criteria for TE Materials

Minimum κ_{ph}

$$\kappa_{ph} \approx \kappa_{\min} \approx 0.2 \frac{W}{m-K}$$

Maximum TEP

$$\alpha_{SC} \approx \frac{k_B}{e}\left(\frac{E_G}{2 k_B T}\right) > 200 \frac{\mu V}{K}$$

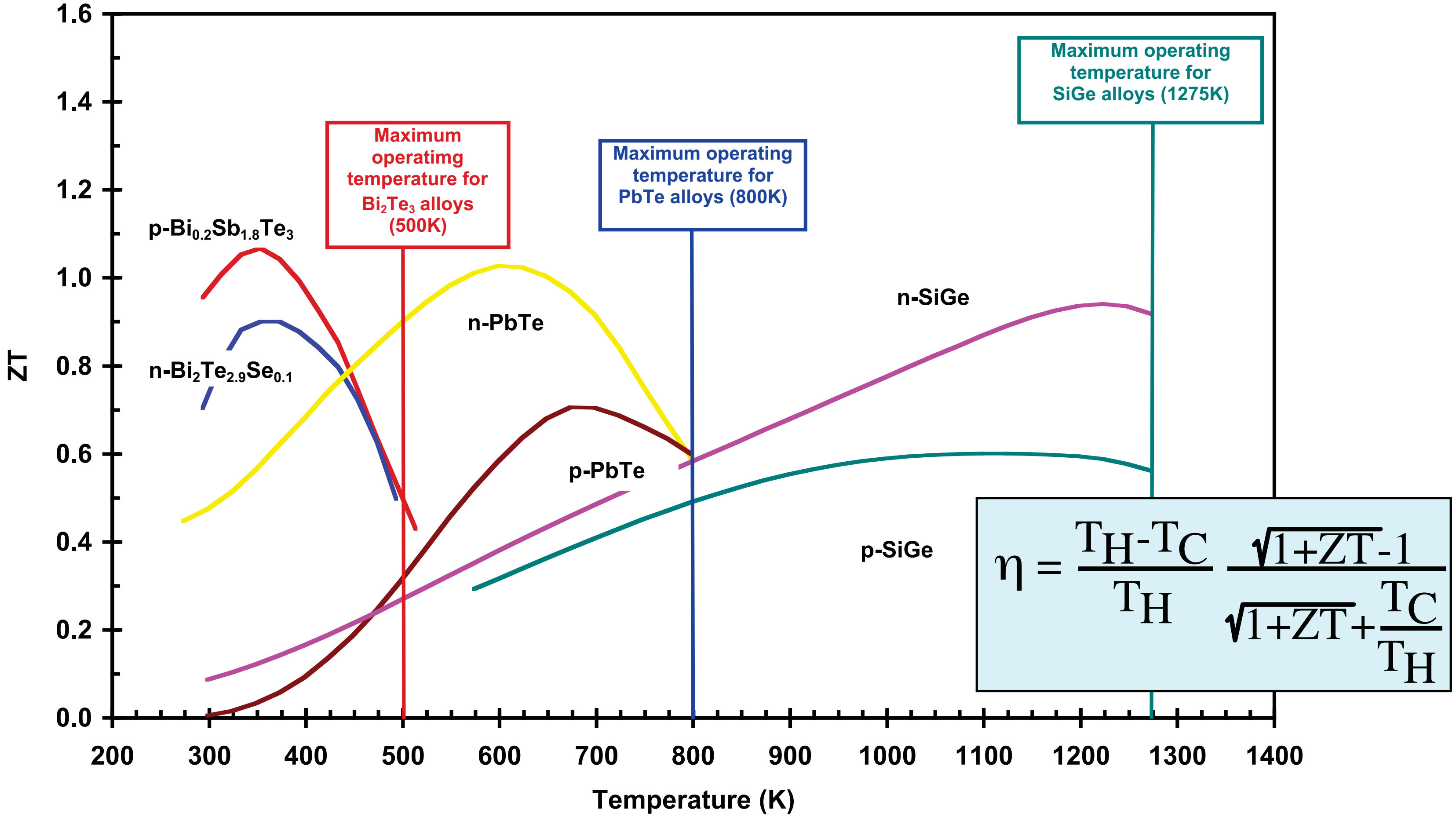
High Weighted mobility

$$U_M = \mu \left(\frac{m^*}{m_e}\right)^{3/2} \approx 750 \frac{cm^2}{V-s}$$

Other Critical Issues to consider:

- Materials Stability over time and temperatures
- Radiation tolerance
- Low Thermal and Electrical Contact Resistances
- Diffusion Barriers
- Thermal Expansion
- Heat Exchangers & Thermal Sinking
- Cost of TE materials

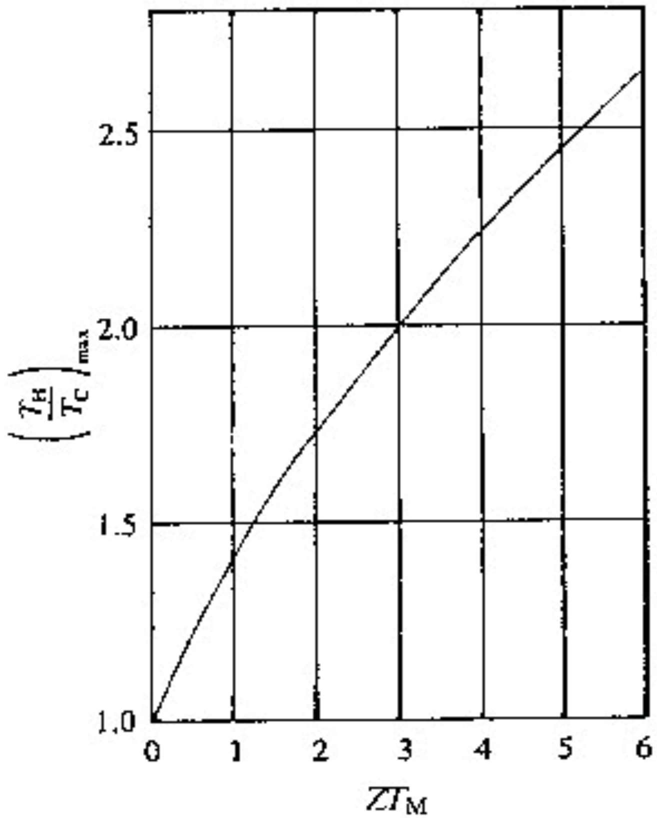
State-of-practice thermoelectric materials

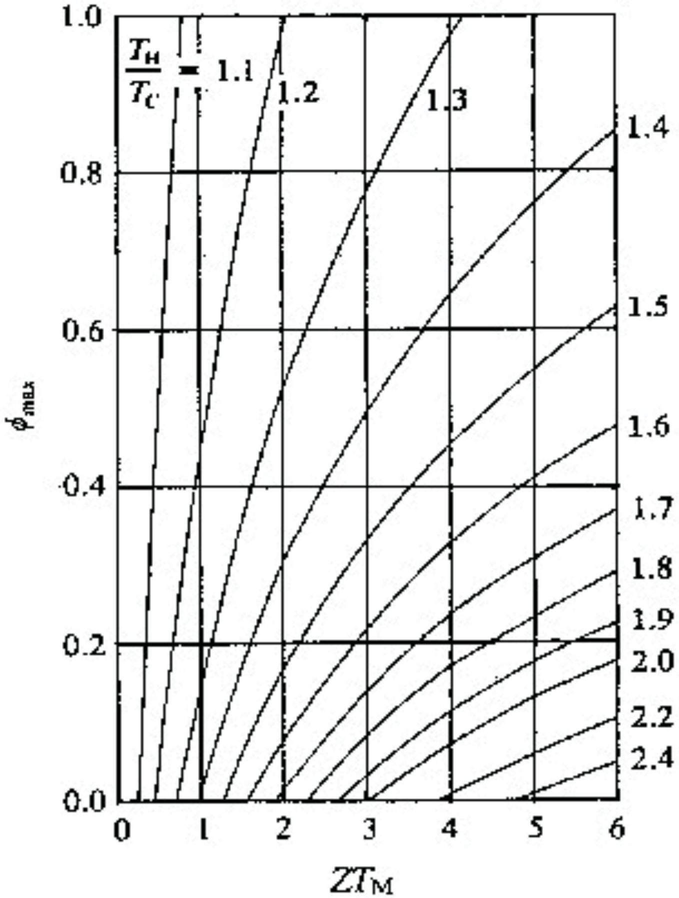


$$\eta = \frac{T_H - T_C}{T_H} \, \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$

TE materials used in commercial applications were discovered in the 1960's

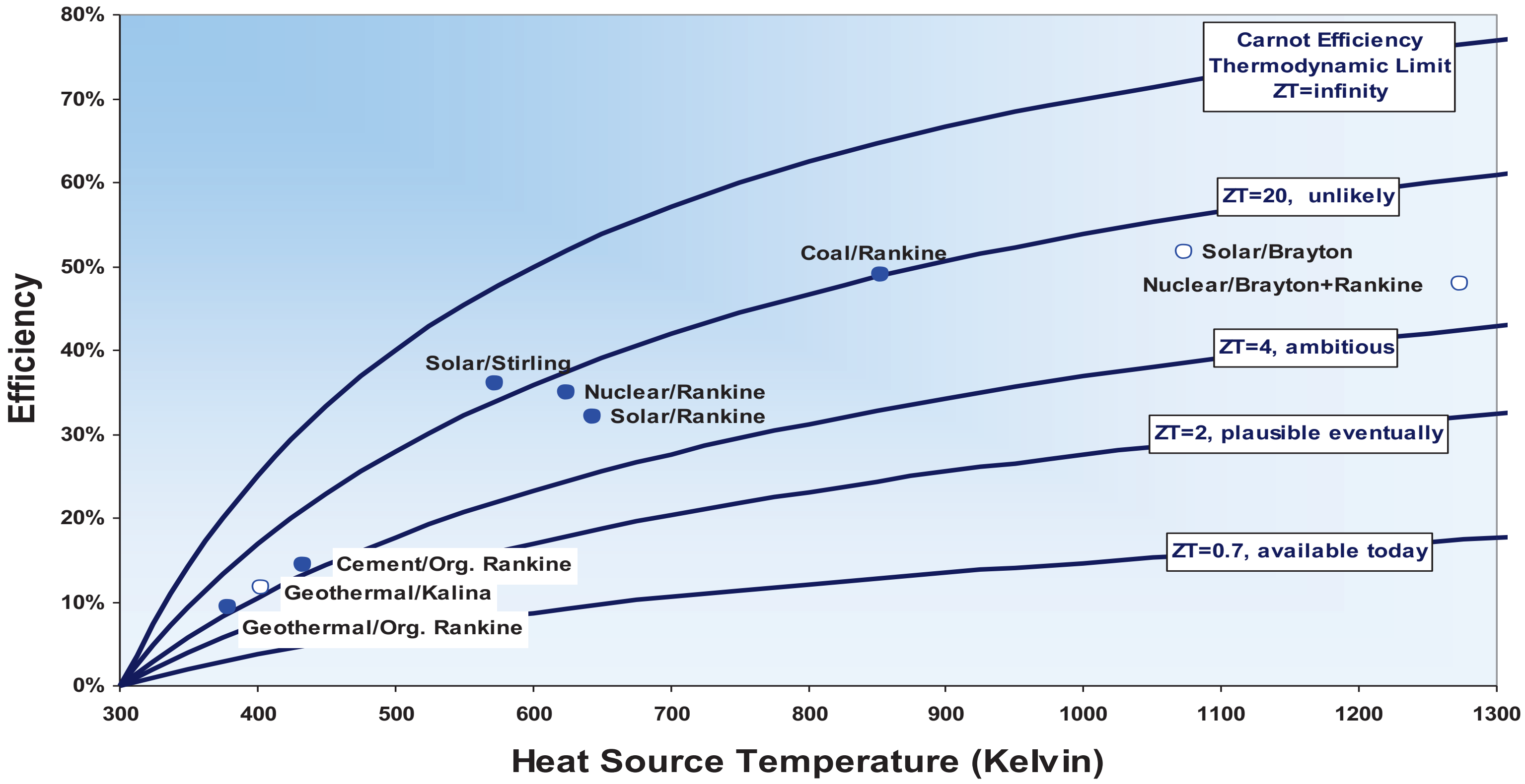
ZT_m vs. COP





- **ZT ~ 3 would be needed for thermoelectrics to compete with vapor compression-based refrigeration systems**
- **Thermoelectrics prevails in niche applications where scalability and reliability are key and not efficiency**

'Best Practice' vs. Thermoelectric Efficiency



- **With current ZT values, thermoelectrics is not competitive with other current conversion technologies**
- **However, thermoelectrics prevails in niche applications where scalability and reliability are key**

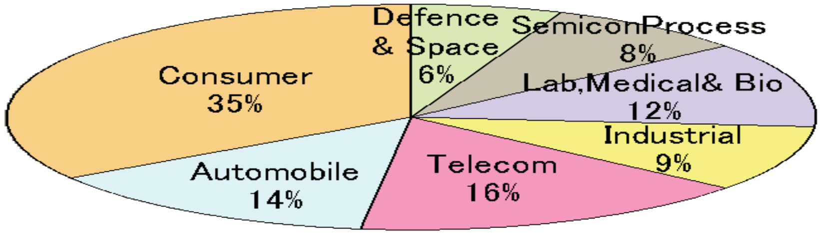
Courtesy of C. Vining

TE Business Status

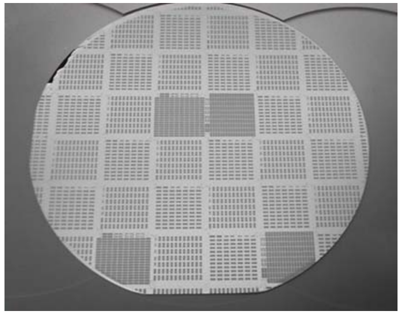
- **Tiny world market for TE power generation**
  - US$25-50M/yr (full systems)
  - [Global Thermoelectric]
- **World market for cooling modules**
  - US$200-250M/yr (modules)
- **New engineering beginning to appear in marketplace**
  - Amerigon (car seat cooler/heater)
  - Sheetak (low cost coolers)
  - Micropelt (miniature devices)
- **Recent materials R&D (ZT) has yet to reach the marketplace**
  - A few are close, for cooling
  - Nextreme (thin film, based on high ZT)
  - GMZ Energy (nano/bulk materials)

TE business today is mainly cooling

500 W TEG, natural gas pipeline, Peru
[LeSage, Global Thermoelectric]



Market Distribution for TE Cooling Modules.
[Komatsu-2007]



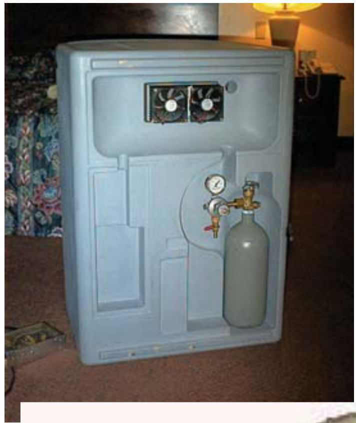
Nextreme (left) thin-film TE cooler and MicroPelt (right) 4" Bi_2Te_3 thin-film TE wafer.

Courtesy of C. Vining

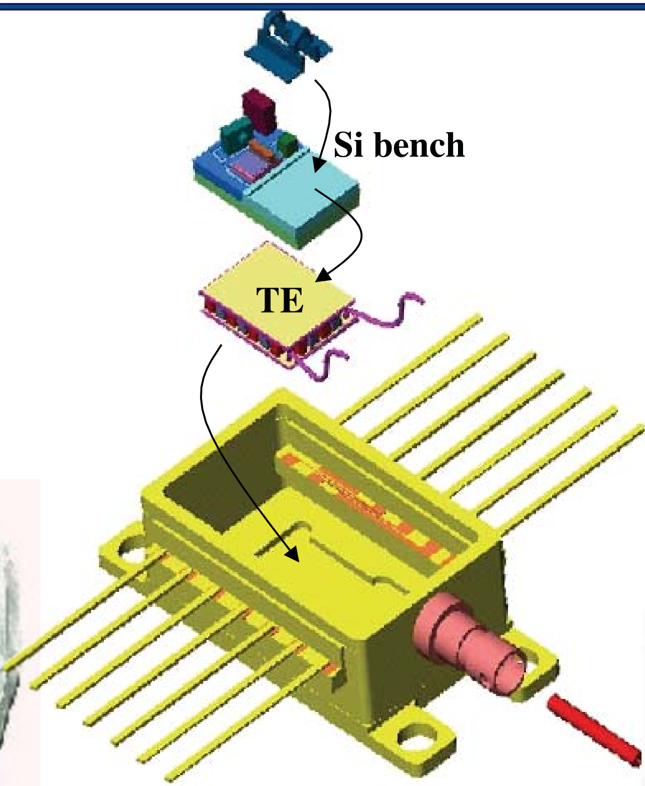
Cooling Applications

Applications

Water/Beer Cooler



Cooled Car Seat



Laser/OE Cooling

Cryogenic IR Night Vision

Electronic Cooling

Bi_2Te_3 modules

USS DOLPHIN AGSS 555

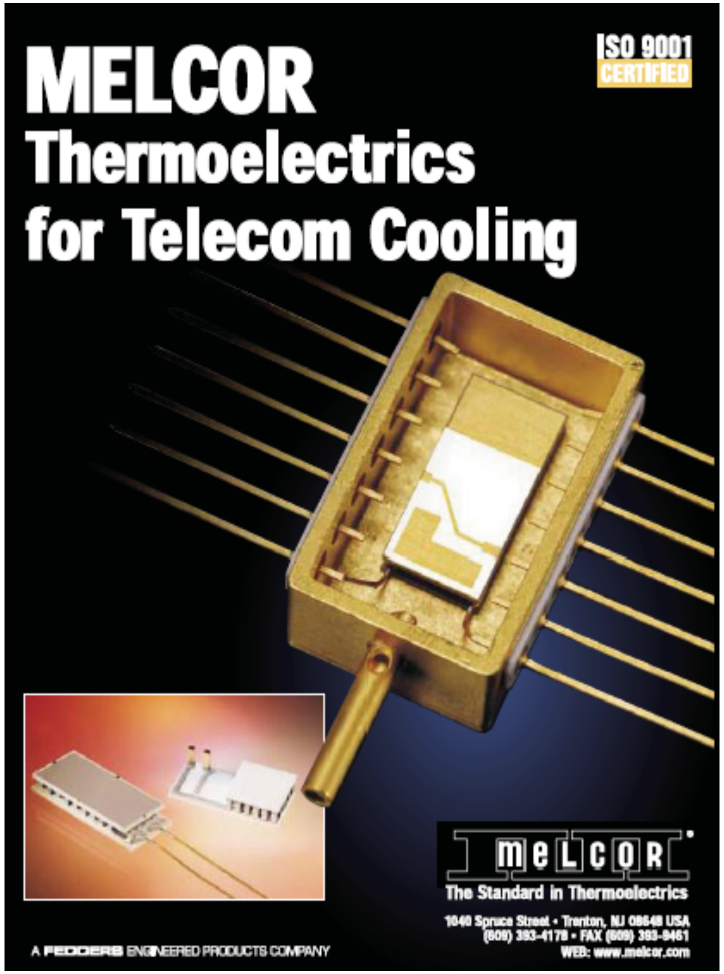
Uses Thermoelectric Air Conditioning - Test for Silent Running

- **Solid-state, silent cooling is attractive for the Navy**
- **ZT values not high enough yet to be practical though**

TEs for Telecom Cooling

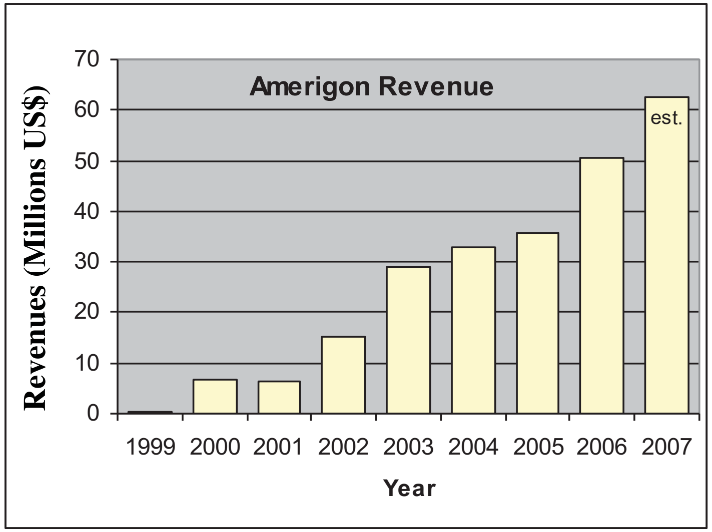
- **Melcor, Marlow and many other TE manufacturers provide coolers specifically designed for Telecom laser-cooling applications**

From Melcor, http://www.melcor.com



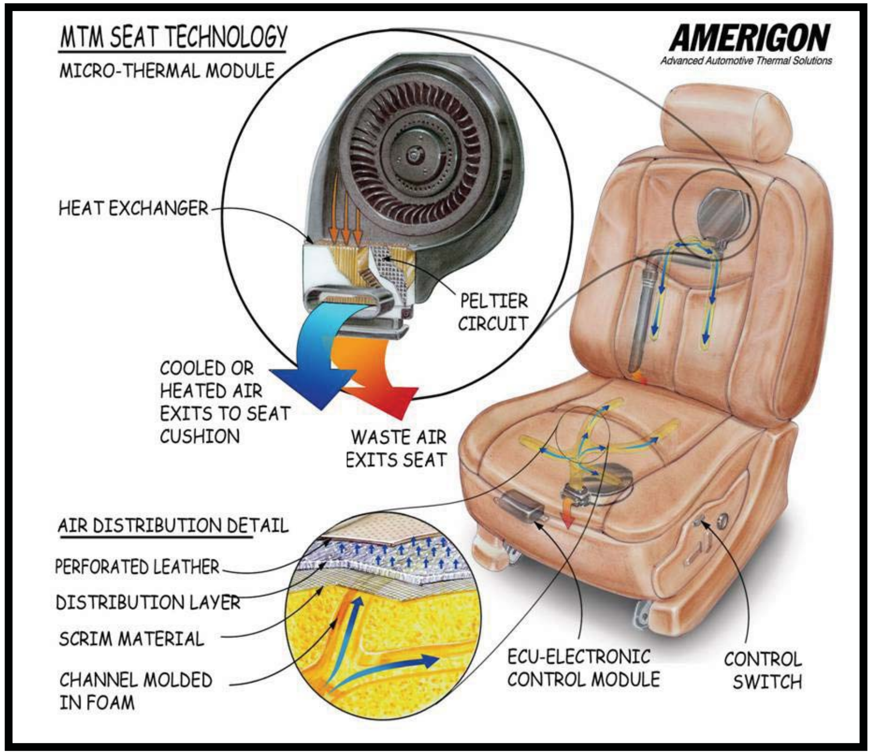
Higher ZT = better, cheaper

Business Developments

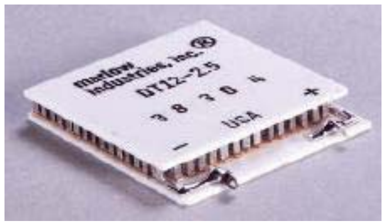


Amerigon revenue 1999-2007

- ‘Old’ Bi_2Te_3 TE materials
- Innovative engineering
- Reduced costs
- Can be used in other new products



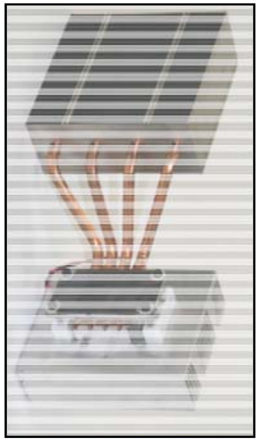
Amerigon: Climate Control Seat™ (CCS™)
[Bell, Amerigon/BSST]

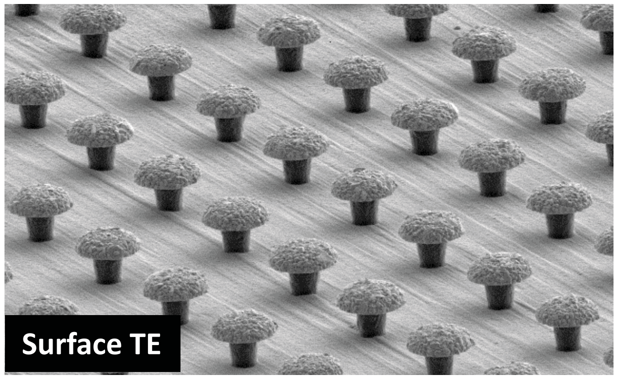


Bi_2Te_3 modules

Business Developments – Sheetak, Inc

- Low-cost coolers
- Innovative thermal management and low-cost TE materials processing



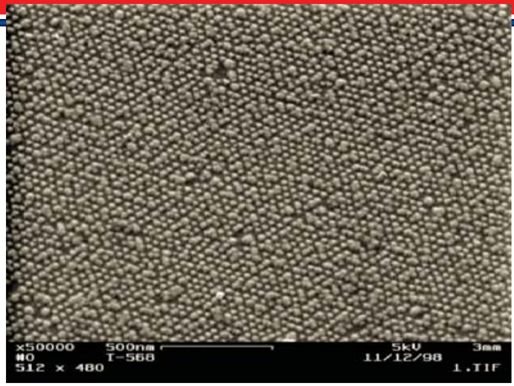


Heat circuits result in 3× reduction in energy consumption

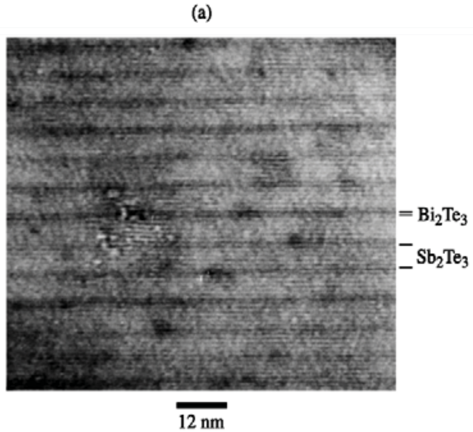
- Low-cost thin-film TE materials processing

Recent development in thermoelectric materials R&D

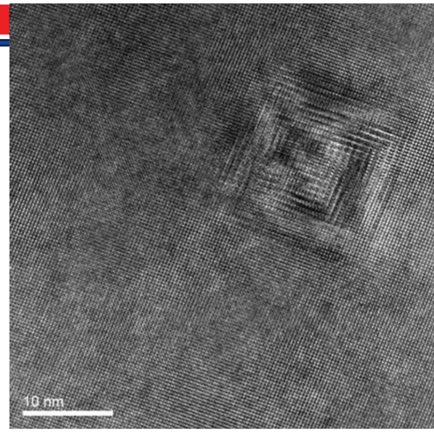
Nano-scale Engineering in Thermoelectrics



ZT~3.5 @ 575 K
quantum dot superlattice (MBE)
n-type, PbSeTe/PbTe
[Harman, MIT-LL, J. Elec.Mat. 2000].

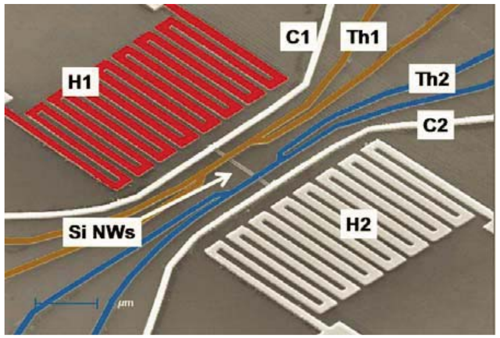


ZT~2.4 @ 300 K
superlattice (CVD)
p-type, Bi_2Te_3/Sb_2Te_3
[Venkatasubramanian, RTI/Nextreme, 2001].

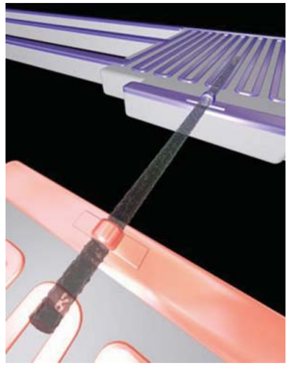


ZT~2.2 @ 800 K
bulk – 'natural' nanodots
n-type, $AgSbTe_2$-PbTe (aka 'LAST')
[Kanatzidis, Northwestern, 2004]

ZT~1.4 @ 373 K
bulk – fine grain
p-type, $(Bi,Sb)_2Te_3$
[15 authors, BC/MIT/GMZ Energy/
Nanjing University, 2008].



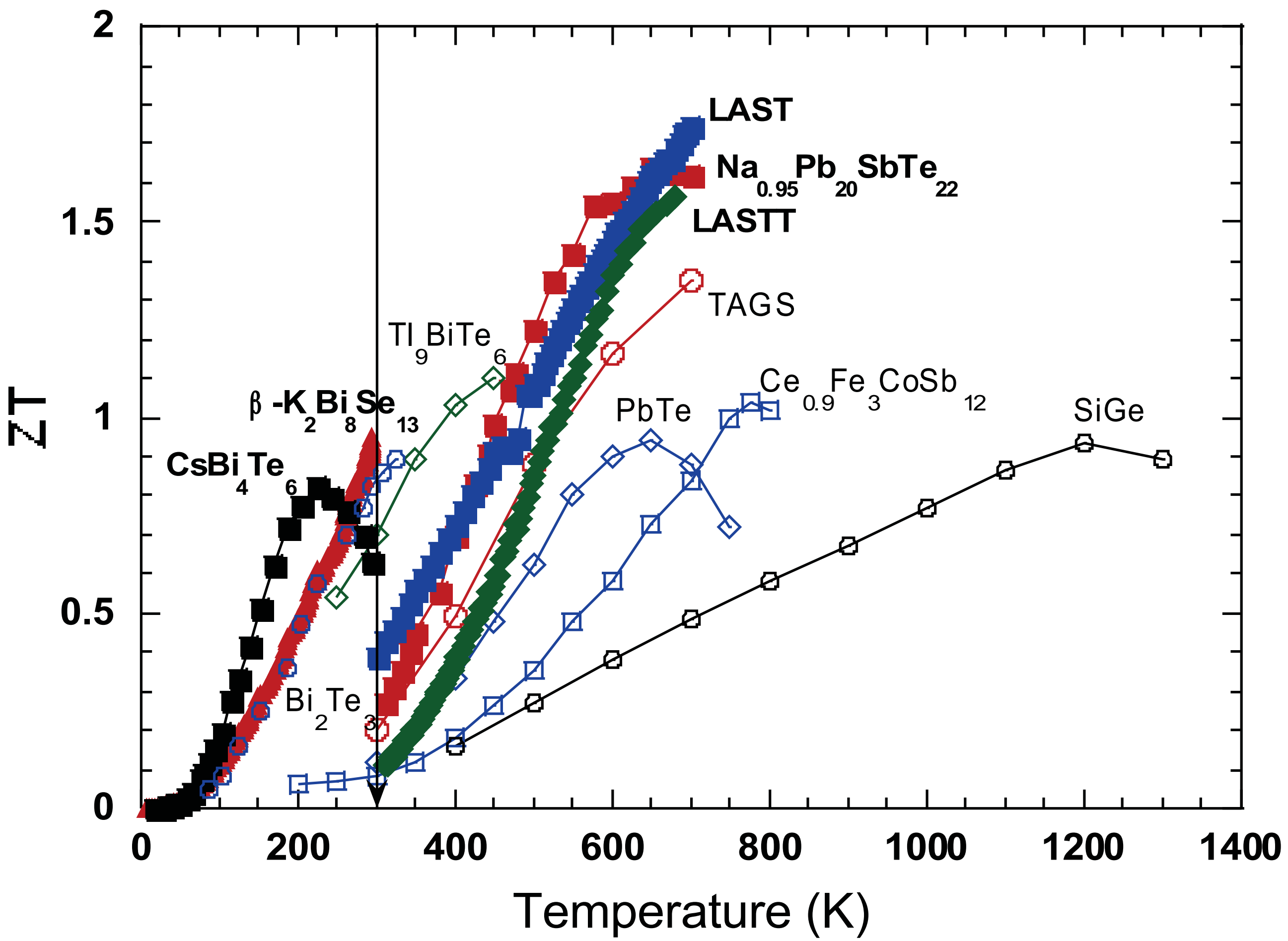
ZT~1.2 @ 350 K
nanowire
p-type, Si
[Heath, Caltech, 2008]



ZT~0.6 @ 300 K
nanowire
p-type, Si
[Yang/Majumdar, Berkeley, 2008]

Recent materials R&D resulted in ZT >1 but advanced cooling materials not quite used for commercial applications yet

Power Generation Materials

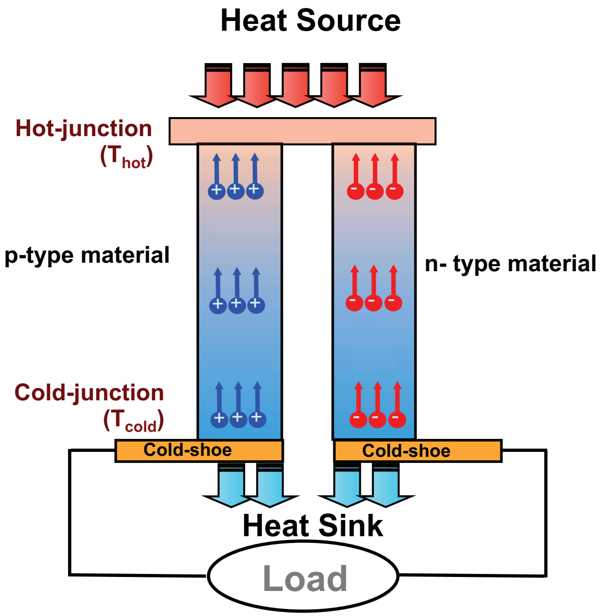


Most new, bulk thermoelectric materials recently developed with ZT > 1 are power generation materials

Power Generation Applications

Thermoelectric Power Generation

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



Thermoelectric Couple

Dimensionless Thermoelectric Figure of Merit, ZT

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

- Seebeck coefficient S
- Electrical resistivity ρ
- Thermal conductivity λ

Conversion Efficiency

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 is function of ZT and ΔT

Governing equations

Efficiency (η)

$$\eta = \frac{I^2 R_L}{Q_K + (Q_P)_H - \frac{1}{2}Q_T - \frac{1}{2}Q_J}$$

Thermocouple conductance

$$Q_K = K\Delta T$$

Total voltage

$$E_0 = \alpha\Delta T$$

Current

$$I = \frac{\alpha\Delta T}{R + R_L}$$

Peltier cooling at the hot-side

$$(Q_P)_H = I\pi$$

Thomson heat

$$Q_T = I\mu\Delta T$$

Joule heat

$$Q_J = I^2 R$$

- R_L : load resistance
- R: thermocouple internal resistance
- π : Peltier coefficient

In an actual generator, there exist numerous electrical and thermal losses; the efficiency equation listed above therefore represents an upper limit

Converter Design & Operation

Heat Source

$$Q_{in} = K_{TE} . A_{TE} / l_{TE} . \Delta T$$

Converter configuration
fixed by required thermal conductance
(cross-section A_{TE} over length l_{TE})

Radiative or Conductive) Coupling to Heat Source

Trade between short l_{TE} and high thermal efficiency

$$A_{TE\ couple} = N_{couple}(A_{p\text{-}leg} + A_{n\text{-}leg})$$

Converter Efficiency

Operating ΔT

ZT determined from Single Stage, Segmented or Cascaded Combination of TE Materials

$$\eta_{max} = \eta_{Carnot} . \eta_{TE\ materials}$$

Radiator for Heat Rejection at T_{cold}

$$Q_{out} = (1 - \eta_{max}) Q_{in}$$

Converter Voltage Output

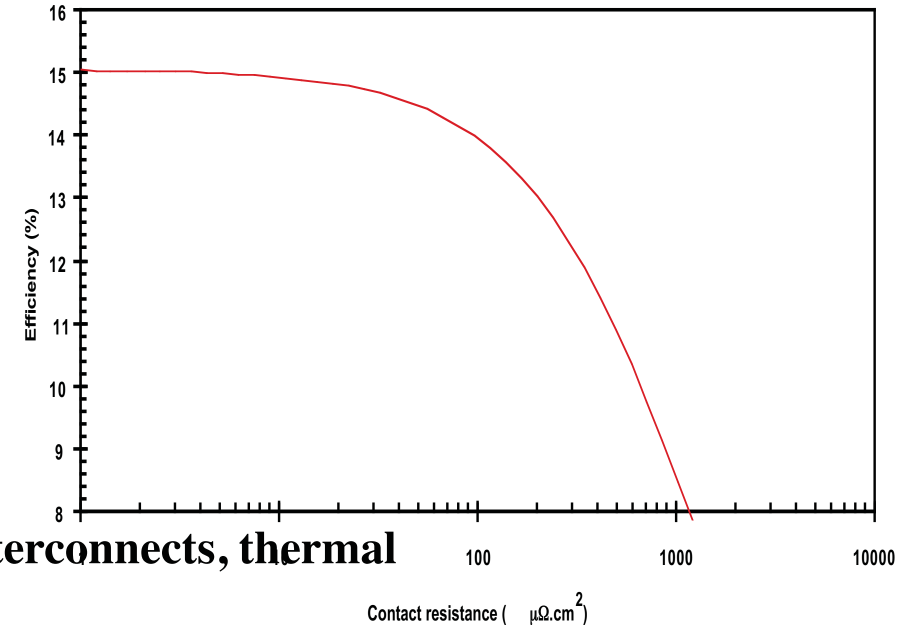
$$V_{RTG} \sim ½(N_{couple} / N_{parallel\ strings}) . S_{TE\ couple} . \Delta T$$

TE couples in series/parallel

Arrays of Unicouples or Multicouples

Device/system design considerations

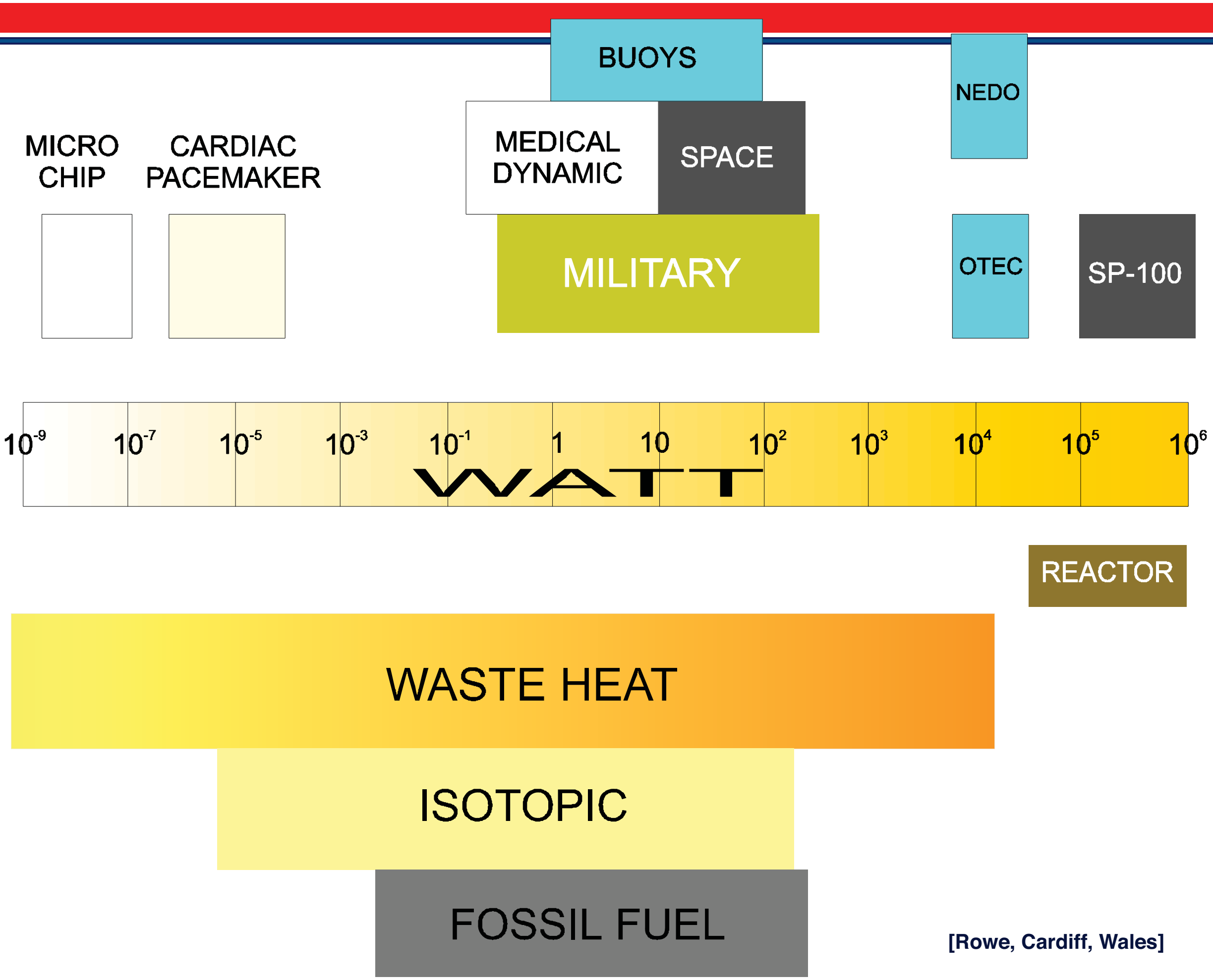
- **Efficiency vs. power output considerations**
  - **Fixed input temperatures - power output and efficiency optimize for different values of R/R_L; P max corresponds to $R = R_L$**
  - **Fixed heat input - power output and efficiency optimize for the same value of R/R_L**
- **Thermal and electrical contact resistances**
  - **Greatly reduces net efficiency**
  - **High-T low electrical contact resistance is a challenge!**
- **Other considerations**
  - **CTE mismatch (thermal cycling)**
  - **TE materials coatings (sublimation)**
  - **Interdiffusion**
  - **Sublimation/contamination from leads interconnects, thermal insulation**
  - **Cost**



- **Hot- and cold-side heat exchangers are key**

Actual design requires to capture all system considerations and trades between engineering and economic factors

TE Power Generation Applications



[Rowe, Cardiff, Wales]

TE power generation (actual + studies) cover > 12 orders of magnitude

Philips Research – Woodstove

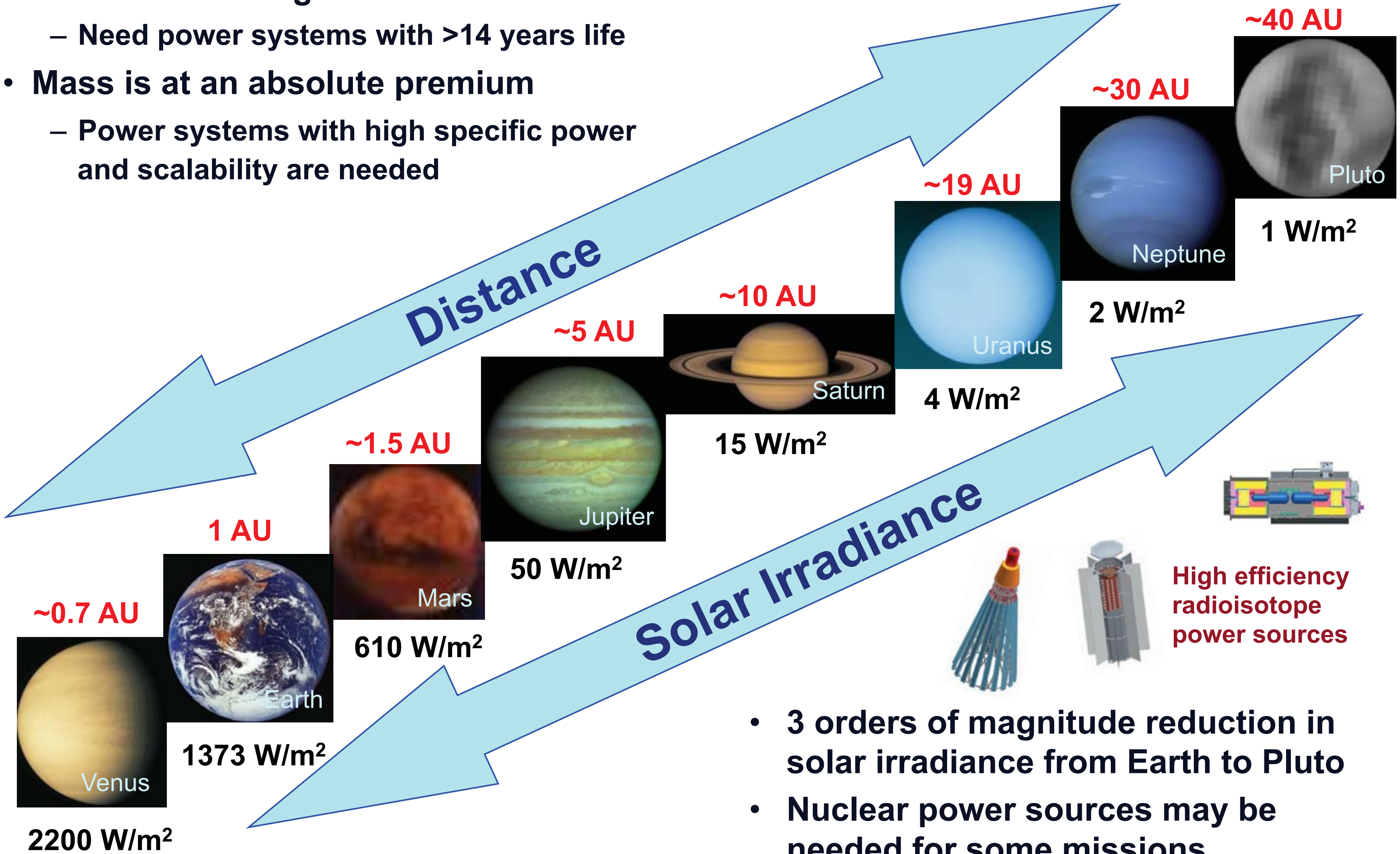
- Paul van der Sluis
  - Philips Research Eindhoven, The Netherlands
- 400 million stoves world wide market
- Pilot of 1000 pieces in India
- TEG powers fan
  - Recharges ignition battery
  - Powers fan – improved combustion

Efficiency unimportant

ILLUSTRATION: BRYAN CHRISTIE

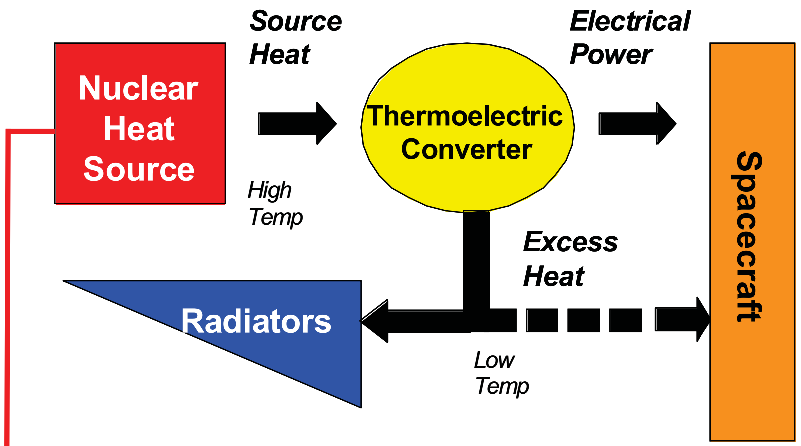
Space Power Technology

- **Missions are long**
  - **Need power systems with >14 years life**
- **Mass is at an absolute premium**
  - **Power systems with high specific power and scalability are needed**

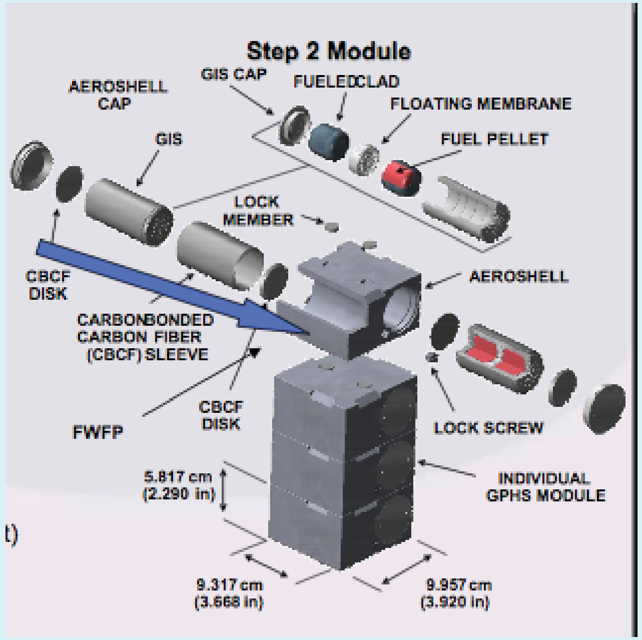


- **3 orders of magnitude reduction in solar irradiance from Earth to Pluto**
- **Nuclear power sources may be needed for some missions**

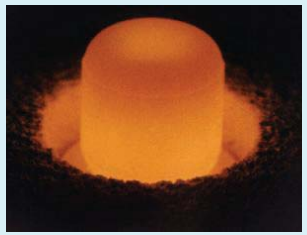
Radioisotope Thermoelectric Generator Key Components



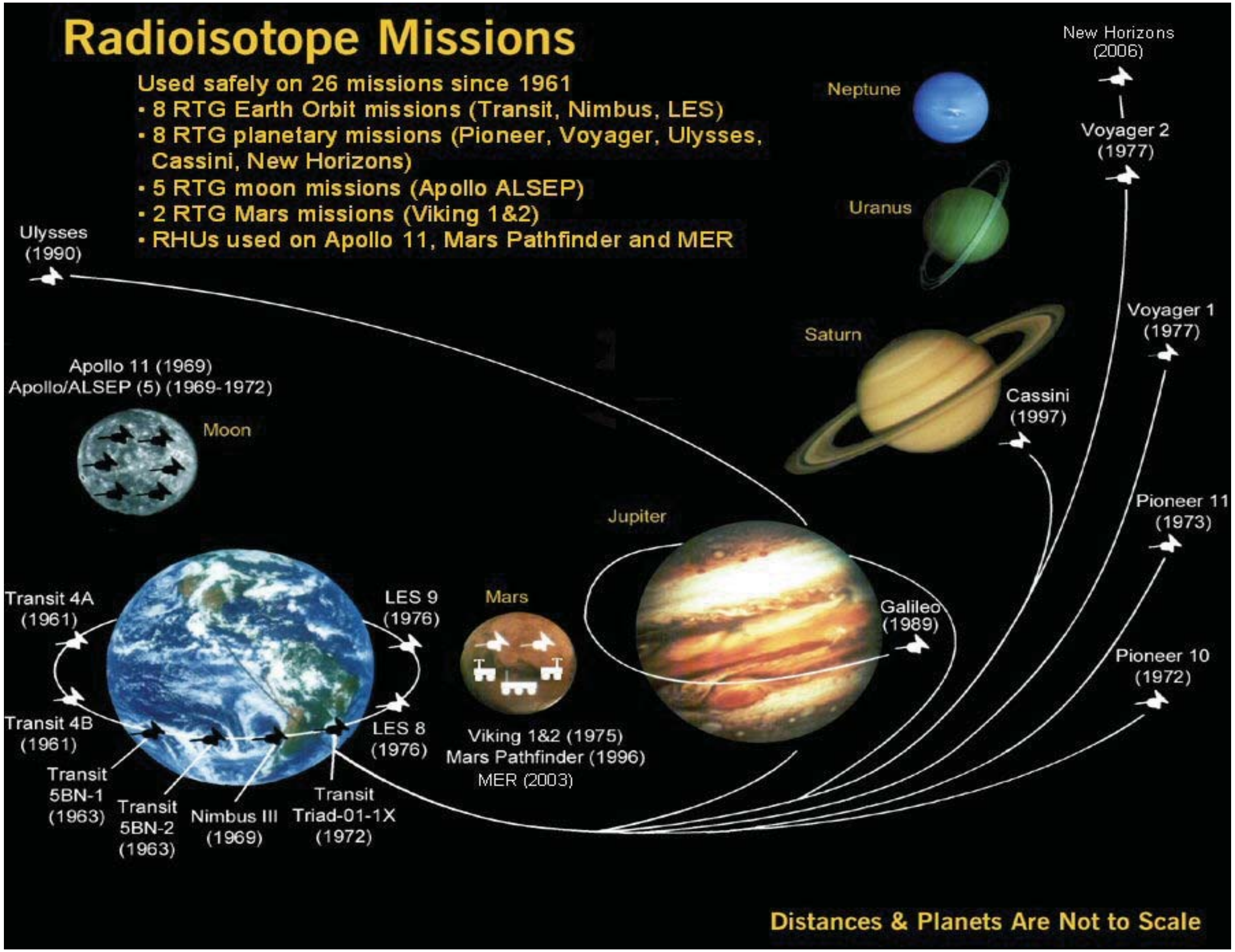
Radioisotope Power System Key Components



- **General Purpose Heat Source (GPHS)**
  - Uses ^{238}Pu
    - Decay
    - α emitter
    - 87.7 years half-life
  - 440 g ^{238}Pu per GPHS
  - 250 thermal Watts/GPHS
  - Heat flux ~ a few W/cm^2
  - $T_H \geq 1275K$

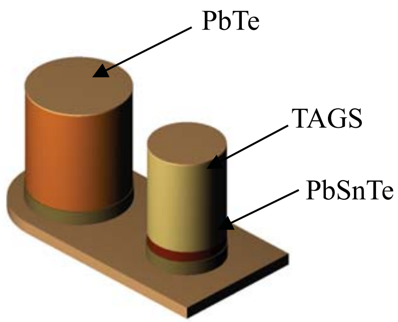


U.S. space missions that have used Radioisotope Thermoelectric Generators (RTGs)

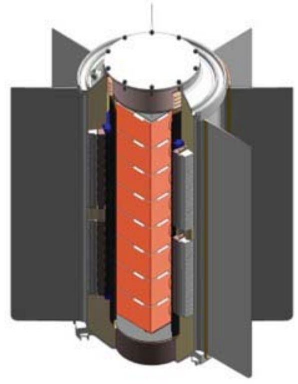


Multi Mission-RTG Characteristics

- Electrical Power Output: ~ 123 W (BOL)
- Specific power: ~ 2.8 W_e/kg
- System Efficiency ~ 6.2%
- Voltage 28 VDC
- In-space & surface operational capability
- Qualified for 0.2 g^2/Hz random vibrations
- Mission life design ~2 years

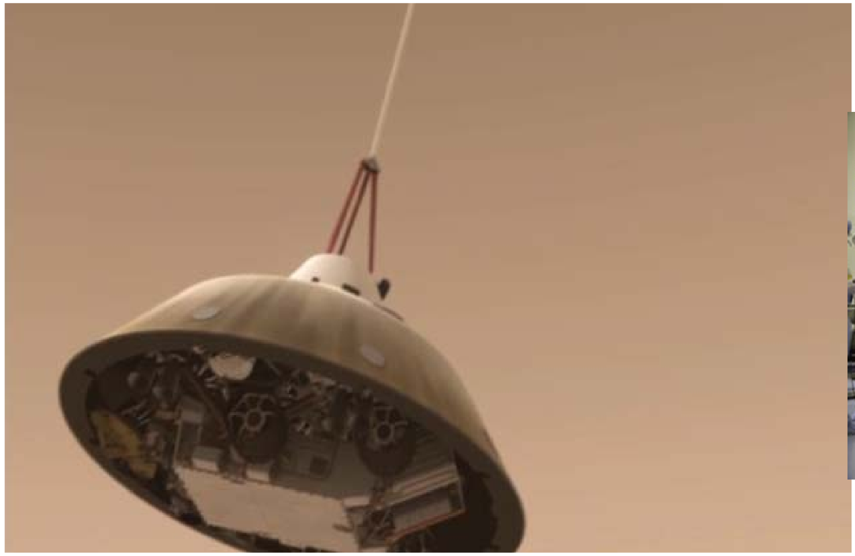


PbSnTe/TAGS+ PbTe couples



MMRTG

- Mass: ~ 44.1 kg
- 8 GPHS modules
- Thermal Power Input ~ 2000 W (BOL)
- 768 PbSnTe/TAGS + PbTe couples
  - T_{hot} ~ 811 K
  - T_{cold} ~ 483 K

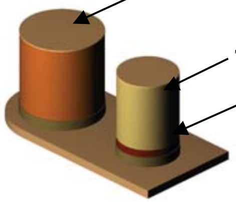


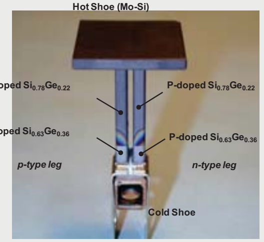
Mars Science Laboratory (MSL)

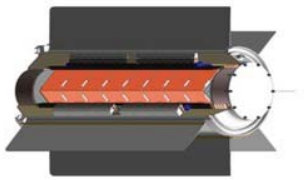
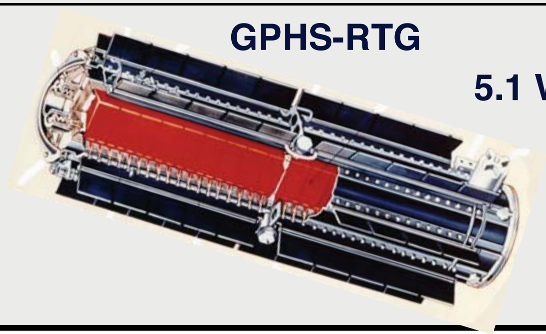
RTG Technology
Key Performance Characteristics

- **Performance characteristics**
  - **Specific power (W/kg) -> Direct impact on science payload**
  - **T/E efficiency -> Reduce PuO_2 needs**
  - **Power output, voltage -> Mission needs**

Couple Efficiency – State-of-Practice

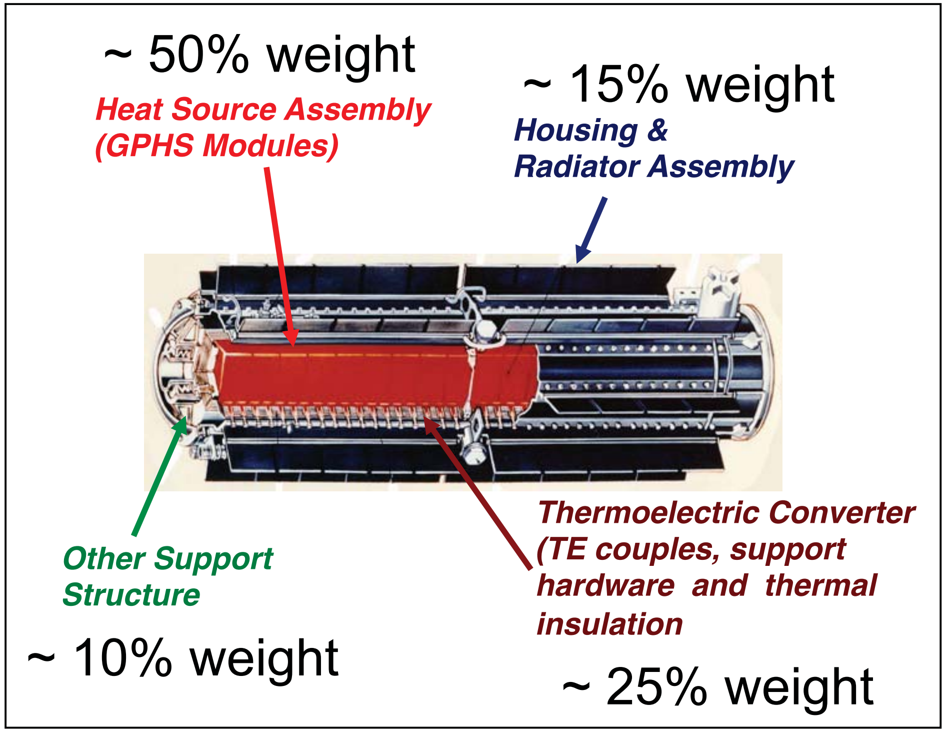
<table>
<tr><th></th><th>N-PbTe</th><th>P-TAGS/PbSnTe</th><th>N- GPHS RTG SiGe</th><th>P-GPHS RTG SiGe</th></tr>
<tr><td>Average ZT</td><td>0.90</td><td>0.84</td><td>0.69</td><td>0.41</td></tr>
<tr><td>Maximum Operating Temperature</td><td>800 K</td><td>675/800 K</td><td>1275 K</td><td>1275 K</td></tr>
<tr><td>Couple Efficiency/ Design</td><td colspan="2">7.0% [800 to 485K]


Conductively coupled</td><td colspan="2">7.5% [1275 to 575 K]


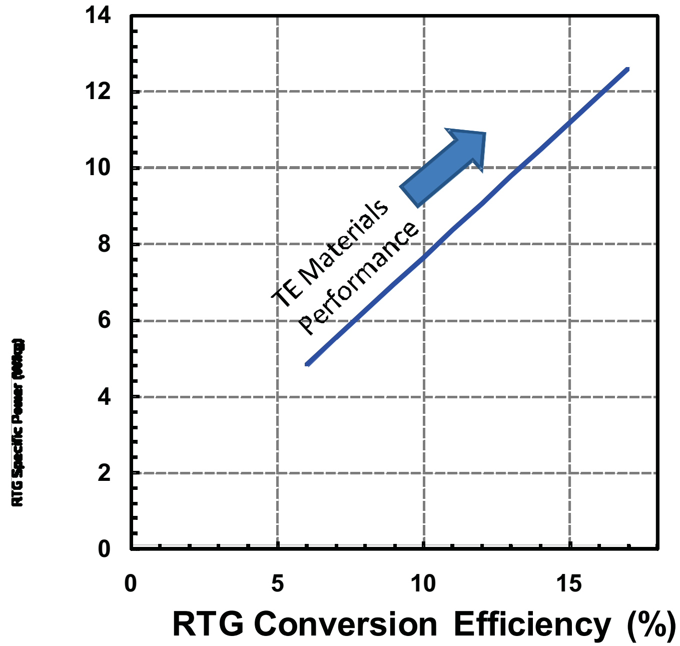
Radiatively coupled</td></tr>
<tr><td>System efficiency</td><td colspan="2">6.2 %</td><td colspan="2">6.3 %</td></tr>
<tr><td>Application</td><td colspan="2">Multi-Mission RTG

2.8 W/kg</td><td colspan="2">GPHS-RTG
5.1 W/kg
</td></tr>
</table>

What Controls RTG Performance?

Most of RTG weight due to heat source and TE converter subsystems



Specific power, efficiency ~ linear relationship

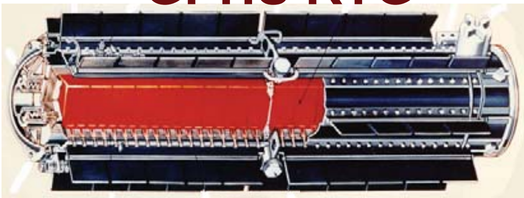
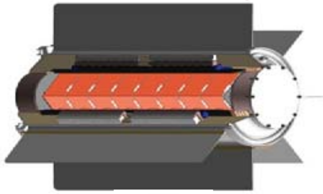


High efficiency TE materials essential to achieve high specific power and reduce usage of PuO_2

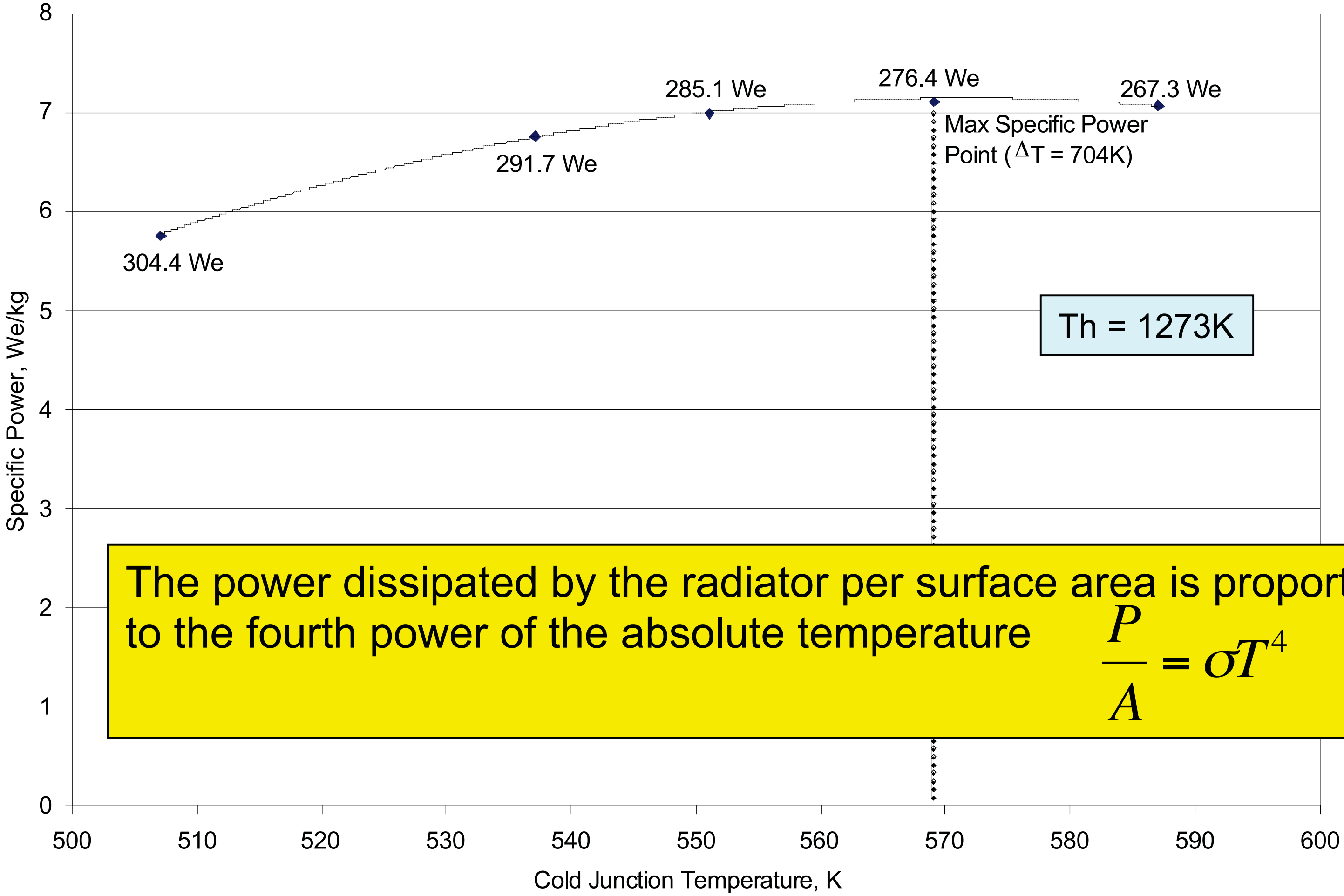
What controls RTGs Lifetime Performance?

Degradation mechanisms

1. Fuel decay
2. Decrease in hot-junction as a result of decreasing heat input
3. Main other mechanisms
   - Thermoelectric properties vs. time & T
   - Sublimation vs. time & T
   - Thermoelectric couple interface electrical contact resistance vs. time & T
   - Thermal insulation vs. time & T

	GPHS RTG	MMRTG
		
1. Fuel decay	~ 0.8%/year decrease in power output	~ 0.8%/year decrease in power output
	+	+
2. Decrease in hot-junction	~ 0.5%/year decrease in power output	~ 0.5%/year decrease in power output
	+	+
3. Main other mechanisms	Decrease in power output: ~ 0.3%/year	Decrease in power output: ~ 2.5/year
Total	Decrease in power output: ~ 1.6%/year total	Decrease in power output: ~ 3.8/year total

Specific power vs. cold-junction temperature

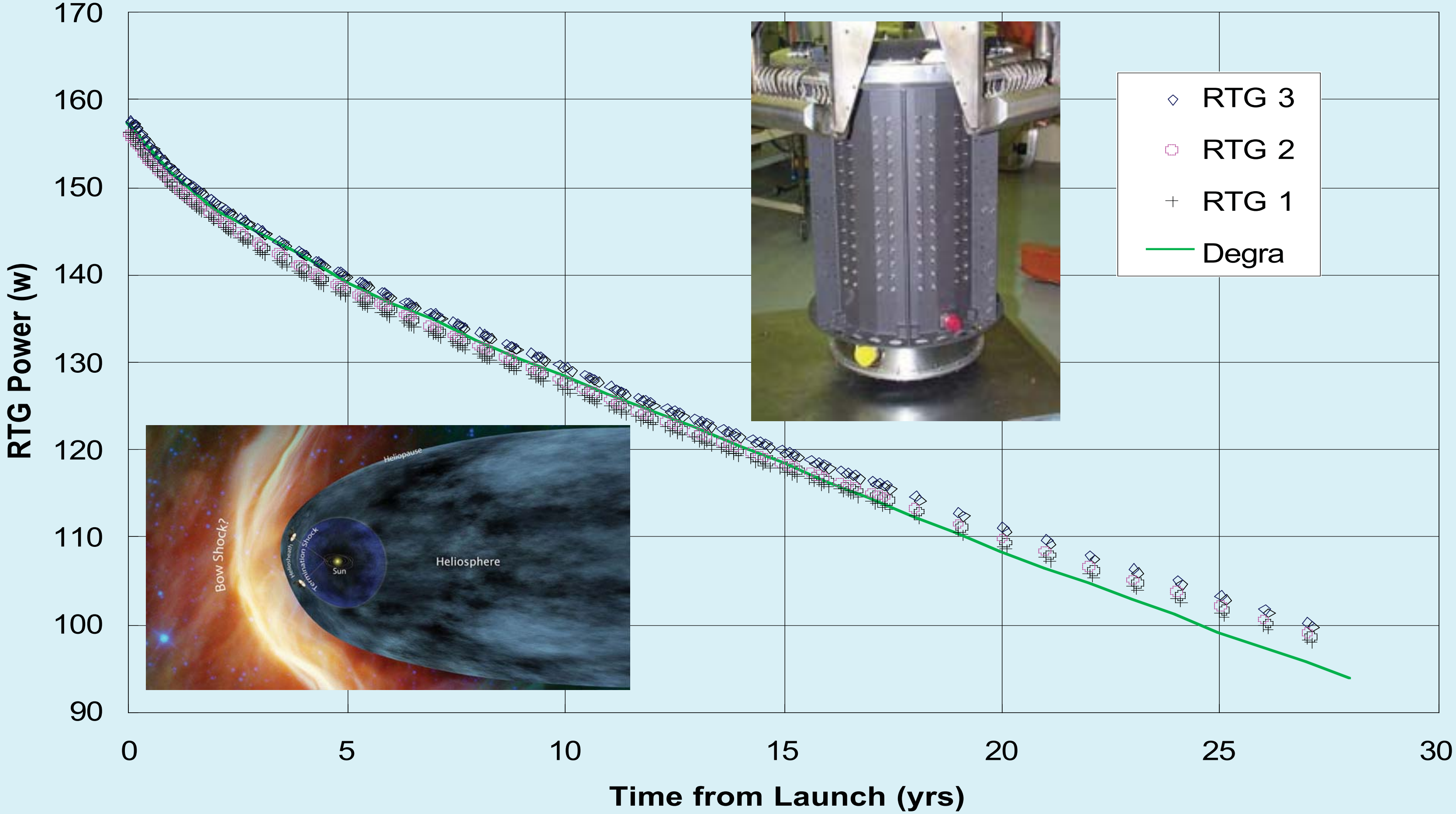


The power dissipated by the radiator per surface area is proportional to the fourth power of the absolute temperature $$\frac{P}{A} = \sigma T^4$$

RTG Technology - Key Benefits

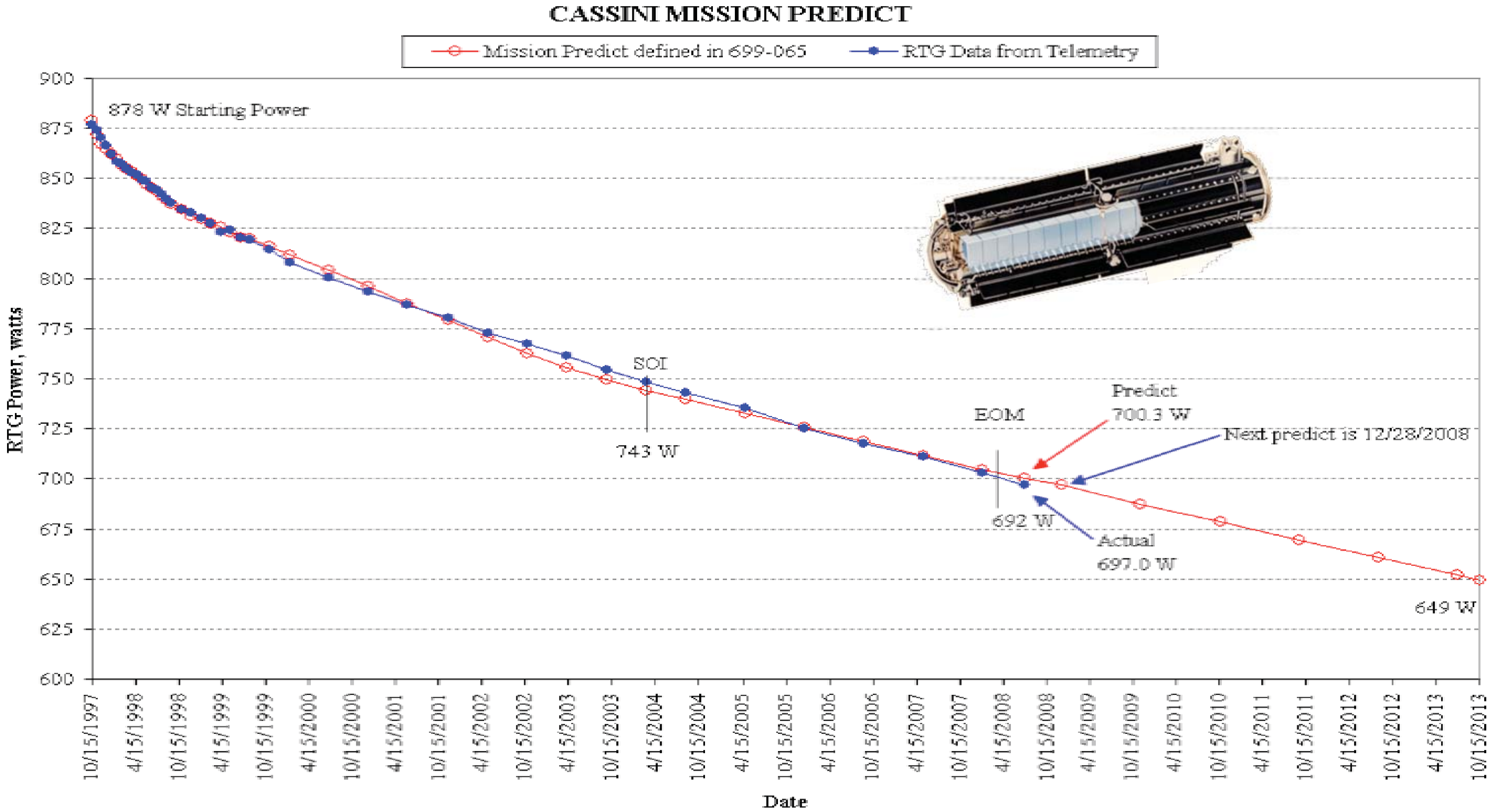
- **Highly reliable with a high level of redundancy**
  - Hundreds of discrete converters in series/parallel configuration
- **Proven long-life operation**
  - Both Si-Ge and PbTe-based RTGs have demonstrated more than 30 years of operation
  - Well known converter aging mechanisms (all solid-state)
  - 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

Voyager MHW RTG Performance



MHRTG's provided power to Voyager I &II for over 30 years reliably

Cassini RTG Performance

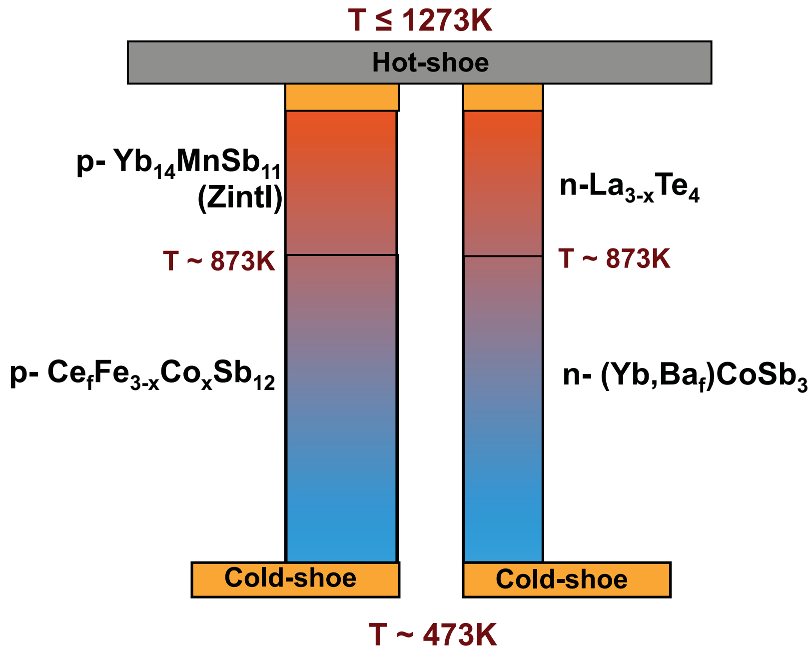


Advanced TE materials and components for next generation RTG

Advanced Thermoelectric Couple (ATEC) Development

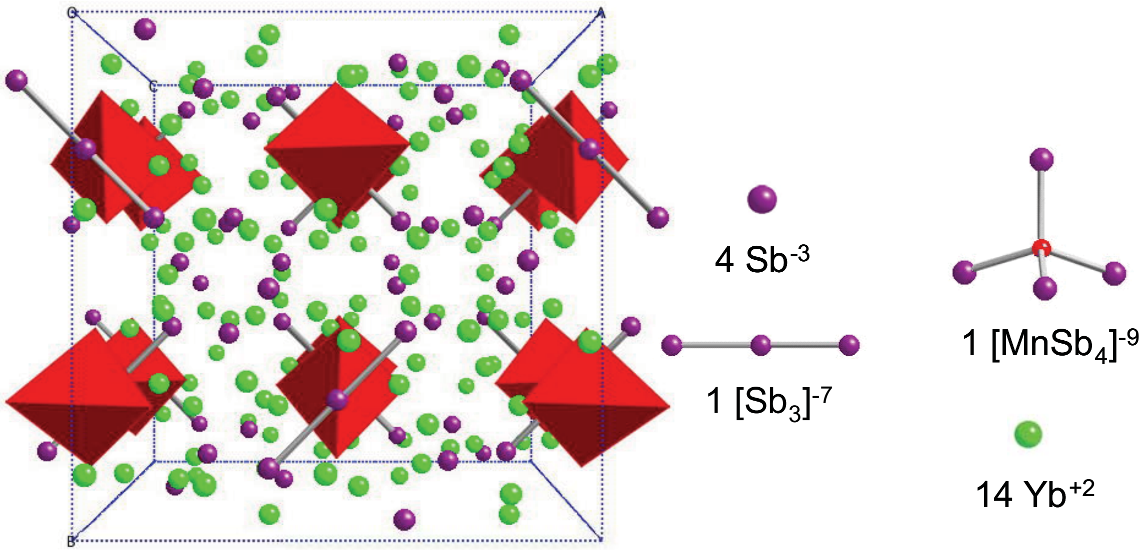
Advanced thermoelectric couples capable of providing:

- **10 - 15% system efficiency**
  (1.5 – 2.5 X over MMRTG)
- **6 - 10 We/kg**
  (2 - 3 X improvement over MMRTG)
- **≥ 17 year life**

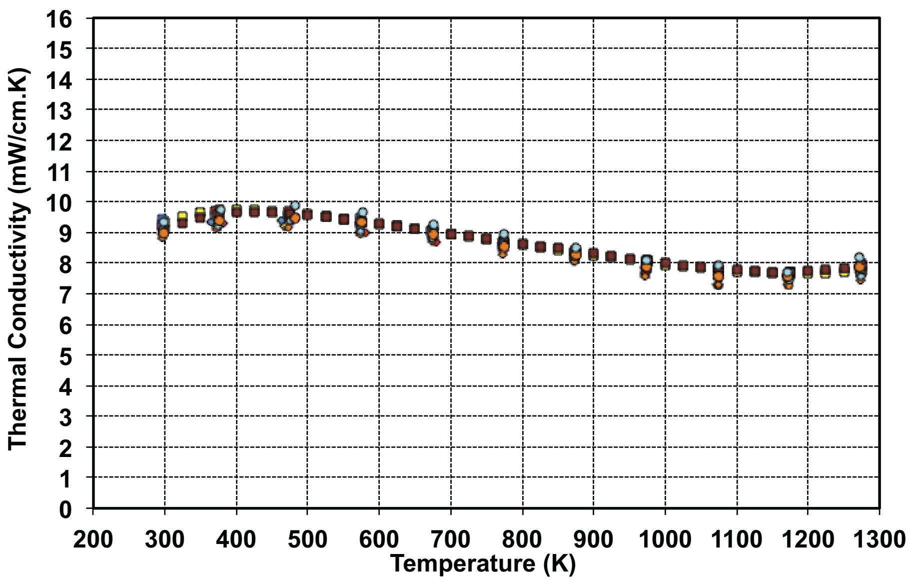


HT TE Materials – 14-1-11 Zintl Phases

- $Yb_{14}MnSb_{11}$ stable to >1300 K
  - ZT > 1 in 1000 -1275K range
  - Many opportunities for doping and disorder
- p-type Zintl compositions derived from $Yb_{14}MnSb_{11}$
  - Yb → Ca, Sr, Eu, La, Ce, Y …
  - Mn → Al, In, Ga, Zn …
  - Sb → P, As, Bi



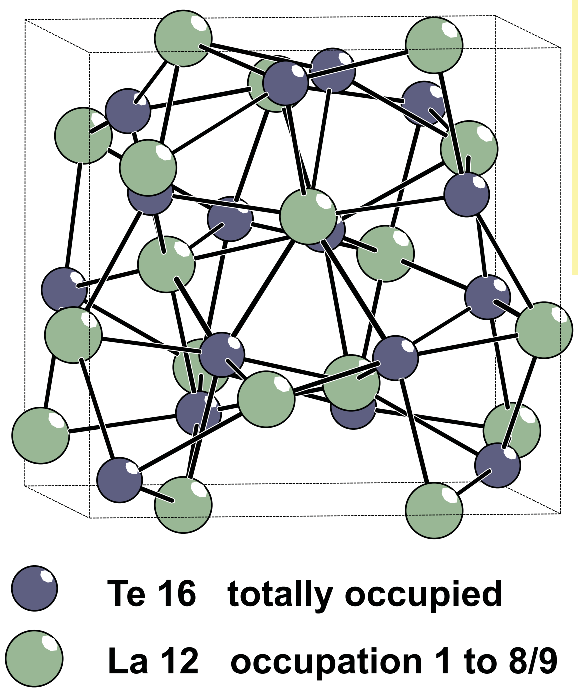
- Tetragonal; I41/acd
  - Z = 8
- Lattice Parameters
  - a = 16.615 Å
  - c = 21.948 Å
- Primary unit cell
  - 1 $MnSb_4$ tetrahedron
  - 1 Sb_3 polyatomic anion
  - 4 Sb^{3-} anions
  - 14 Yb^{2+} cations



$La_{3-x}Te_4$ Structure and Stoichiometry

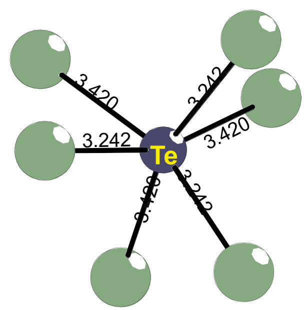
- $La_{3-x}Te_4$: defect Th_3P_4 structure-type (I-43d), up to 28 atoms per unit cell
  - $0 \leq x \leq 1/3$
  - x = 0 ; Te/La = 1.33 ; metallic, electron concentration of ~ 4.49×10^{21} cm^{-3}
  - x = 1 : Te/La = 1.50 ; highly resistive semiconductor (can be written as La_2Te_3)

- $La_{3-x}Te_4 \equiv [La^{3+}]_{3-x}[V]_x[Te^{2-}]_4[e^-]_{1-3x}$
  - $[V]_x$: La vacancy concentration
  - $[e^-]_{1-3x}$: electron concentration
- $La_{3-x}Yb_yTe_4 \equiv [La^{3+}]_{3-x}[V]_x[Yb^{2+}]_y[Te^{2-}]_4[e^-]_{1-3x+2y}$
  - Can independently vary vacancy and electron concentrations



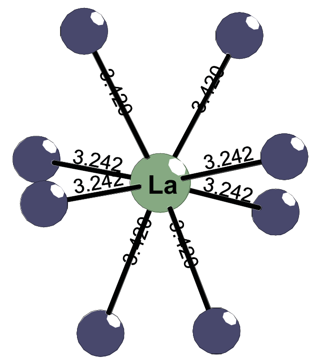
Te 16 totally occupied

La 12 occupation 1 to 8/9



Te environment

Distorted octahedra

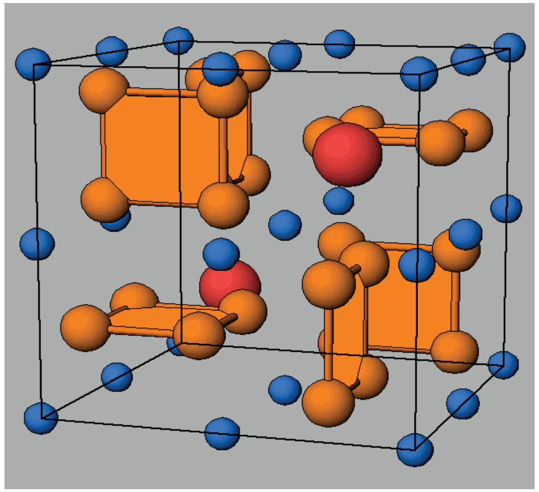


La environment

Pseudo-dodecahedron

Filled skutterudites

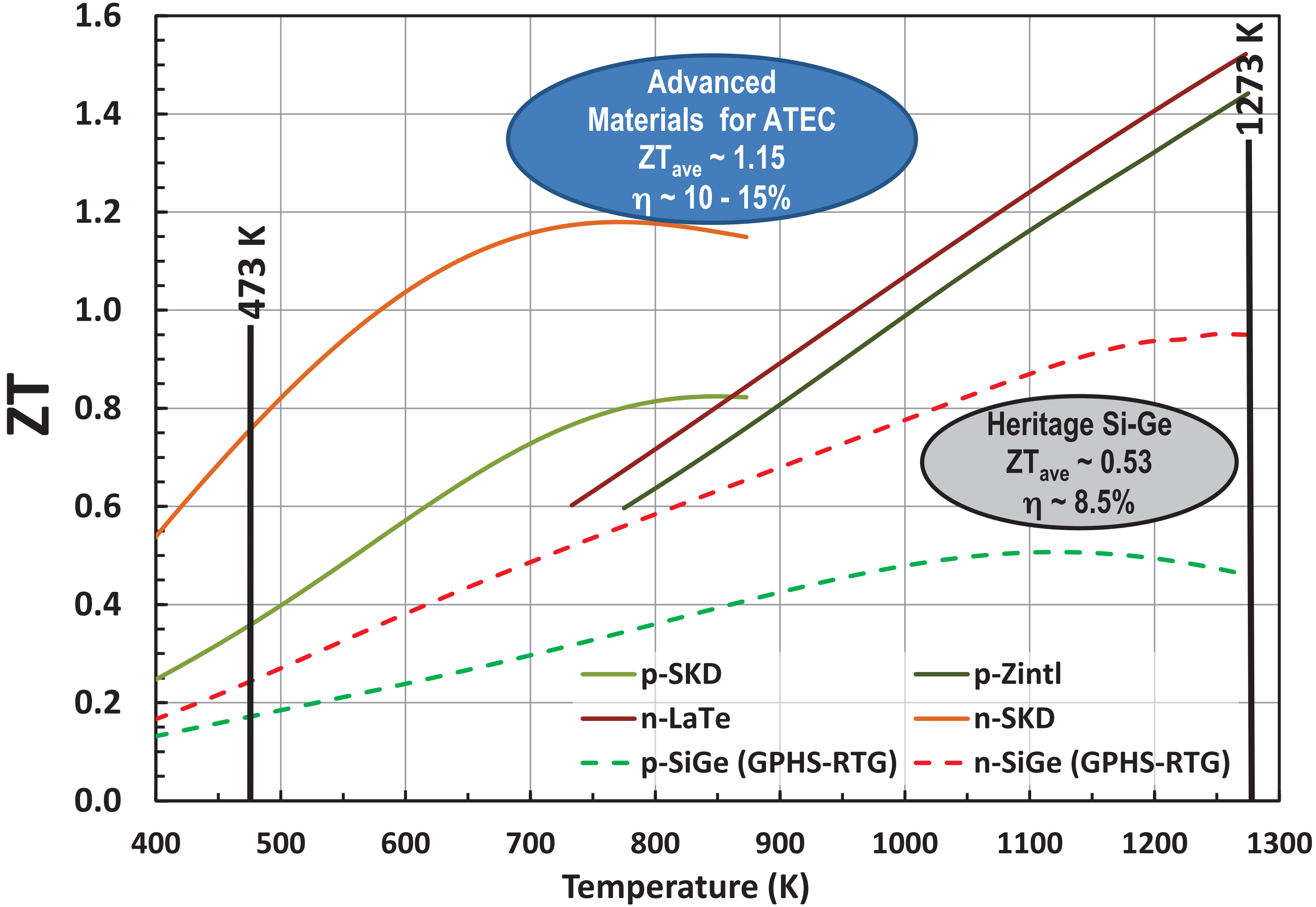
- **Many RT_4Pn_{12} compounds exist such as $LaFe_4As_{12}$**
- **Derived from $CoAs_3$ skutterudite prototype:**
  - By filling the empty octants present in the unit cell
- **Most have a metallic behavior**
  - Trivalent rare earth (La^{3+}) and divalent transition metal (Fe^{2+})
  - Valence electron count (1x3) + (4x8) + (12x3) = 71
  - Count of 72 needed to conserve a semiconducting behavior
- **Expected reduction in lattice thermal conductivity**
  - "Rattlers"
  - Conduction in valence band dominated by Sb rings ; potentially, no significant impact on carrier mobility
  - ⇨ Phonon Glass Electron Crystal (PGEC) concept (G. Slack): decoupling of electrical and thermal transport i.e. conduct electricity like a perfect crystal with a glass-like thermal conductivity



Skutterudite crystal structure

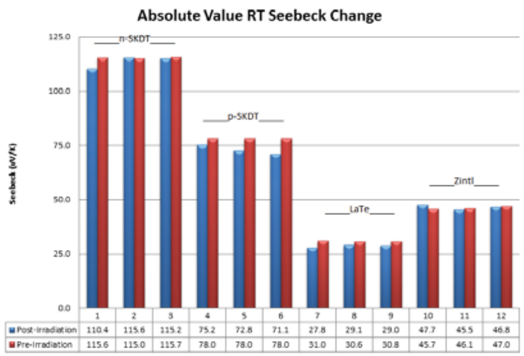
$CoAs_3$ ores

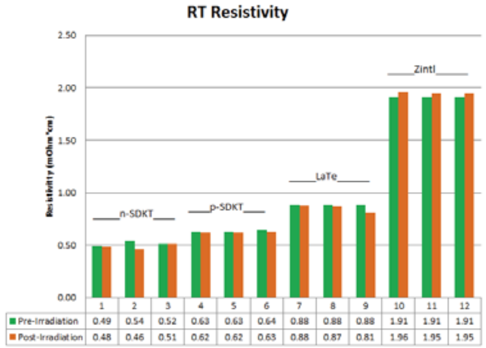
ATEC advanced TE Materials



Neutron Irradiation of TE Materials

- **Observe the impact of neutron radiation on the thermoelectric properties of $La_{3-x}Te_4$, $Yb_{14}MnSb_{11}$, n- and p-type skutterudites**
  - **Neutron emitter Pu-240 is a contaminant in Pu-238**
- **3 samples of each were exposed to 17 years worth of neutron radiation in 35 minutes at the Ohio State University Research Reactor (OSURR) (near room temperature).**





No significant change in room temperature electrical properties

- **ATEC TE materials do not appear to be sensitive to exposure to neutrons**

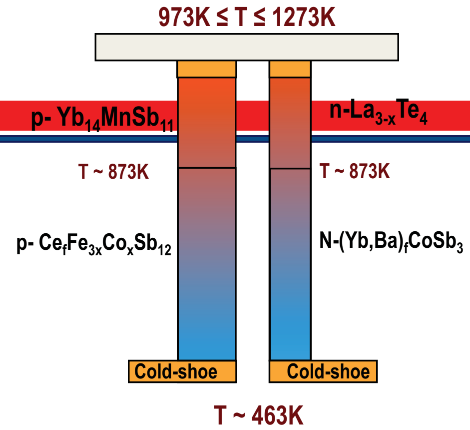
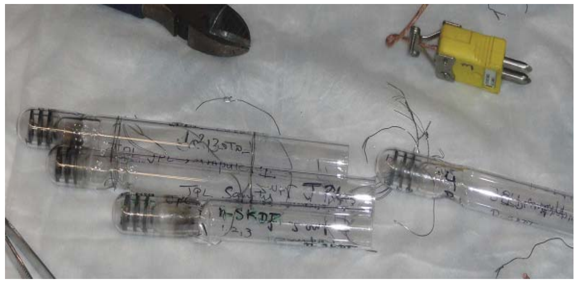
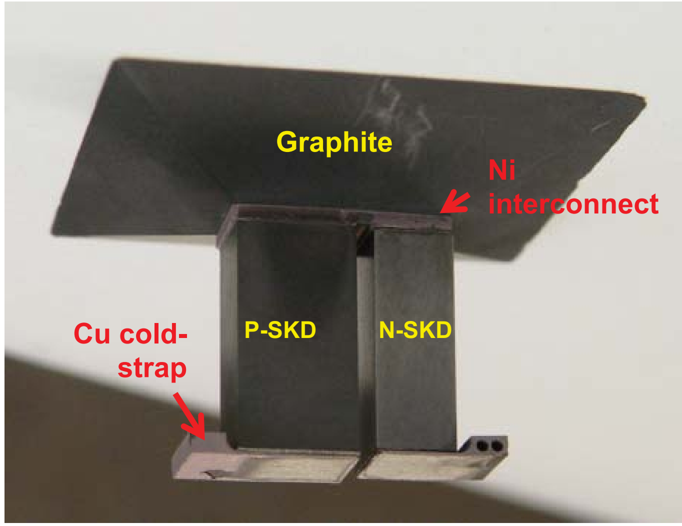


Illustration of ATEC couple under development

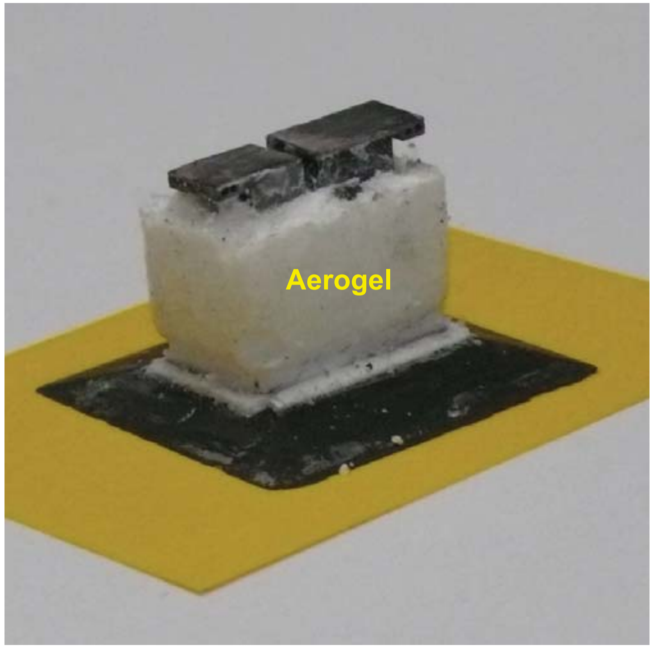


Sample ampoules for irradiation

SKD couple

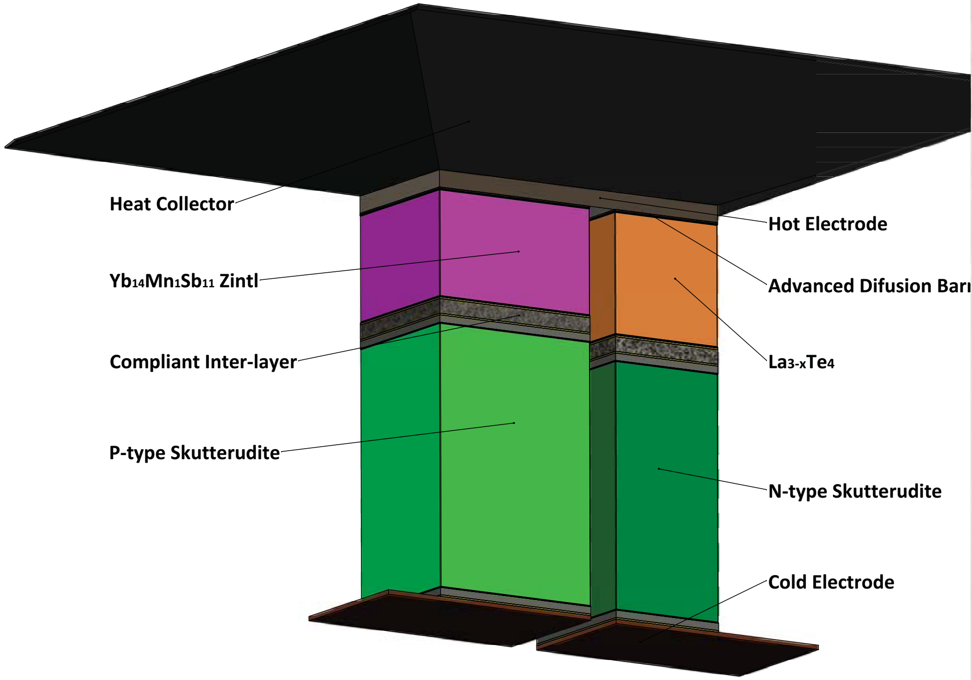


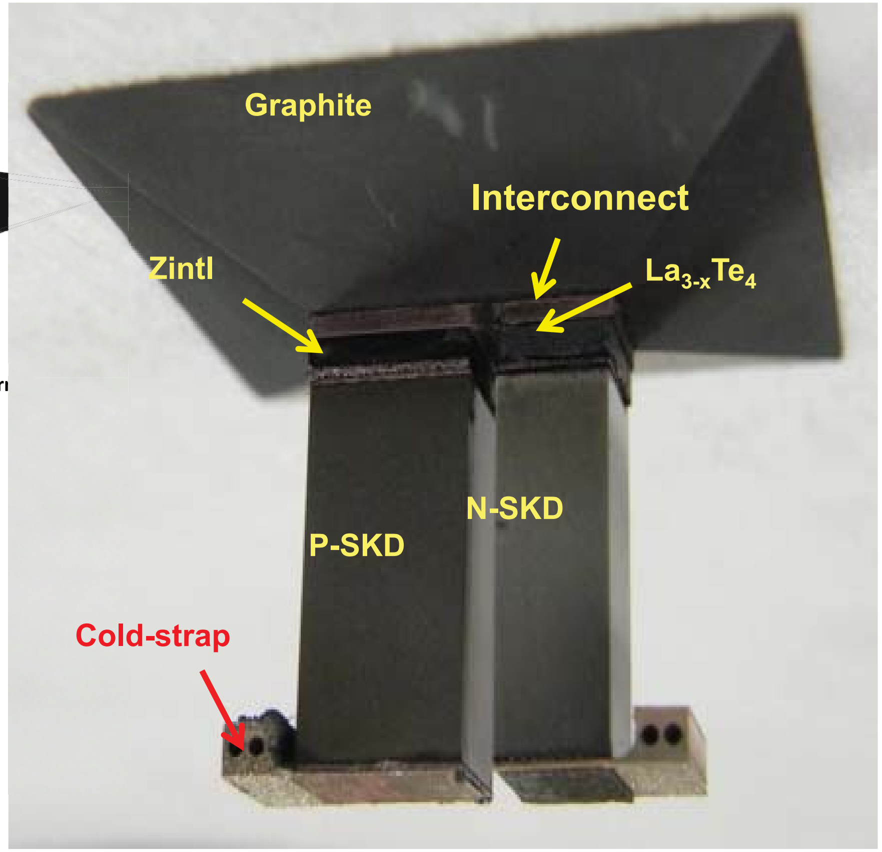
- **Skutterudite couple**
  - (~ 9.3% efficiency – 873K-473K)



- **Skutterudite couple encapsulated with aerogel**

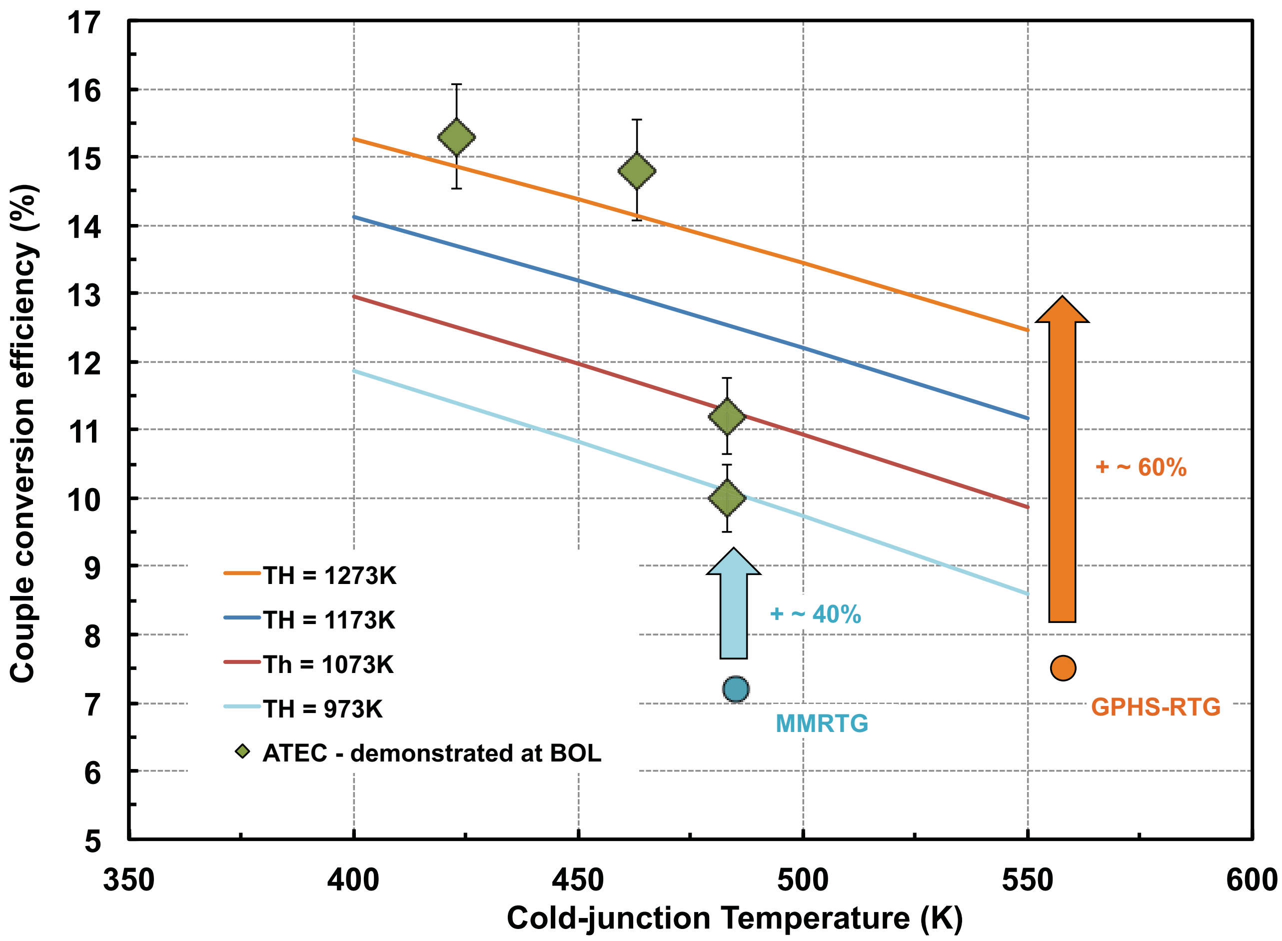
Zintl/LaTe/SKD ATEC couples





	14-1-11 Zintl (p)	$La_{3-x}Te_4$ (n)	Skutterudite (p & n)
Temperature dependent mechanical properties	CTE: 16-19 ppm	CTE: 17-20 ppm	CTE: 12-14 ppm

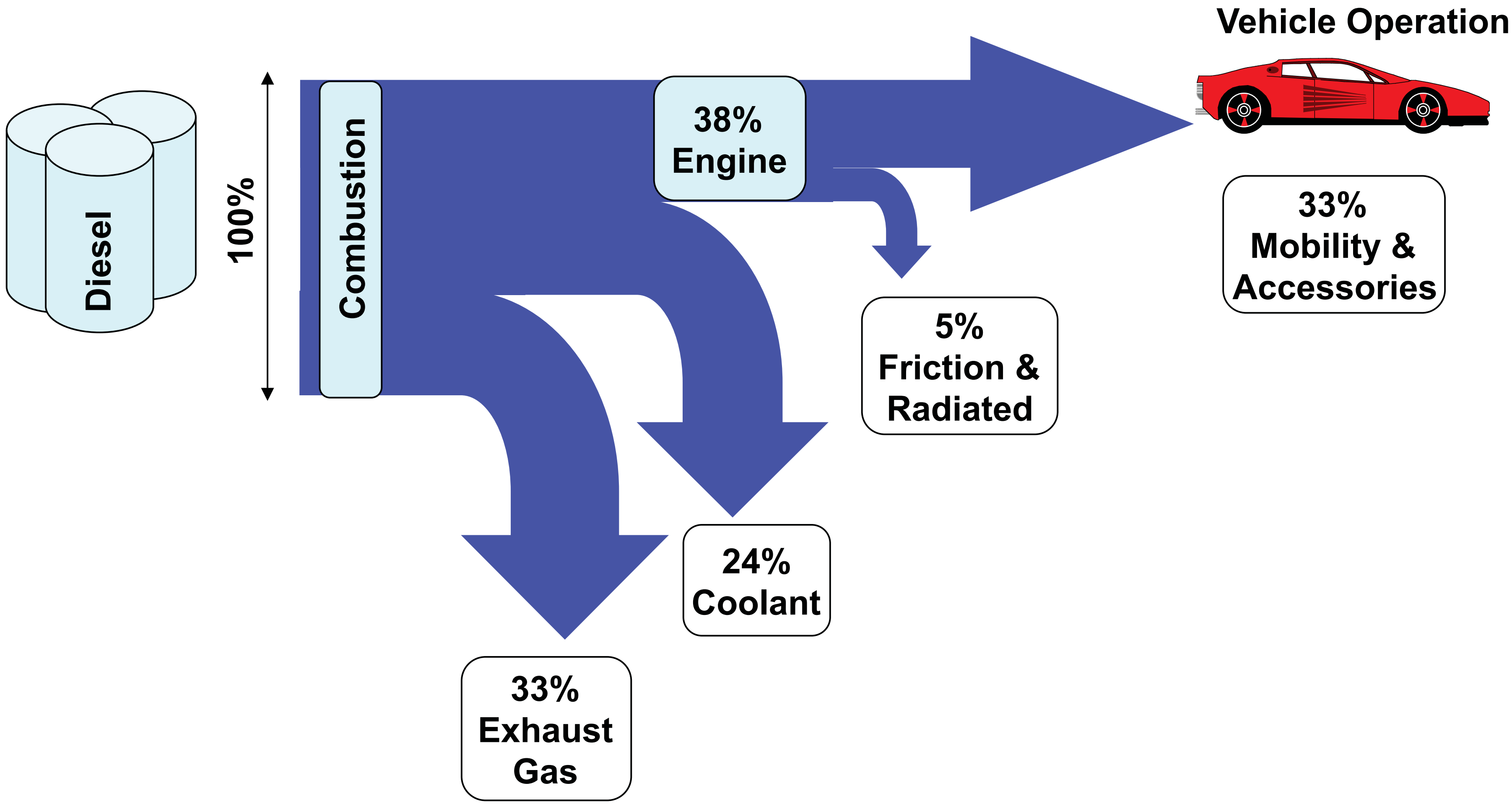
Demonstrated BOL efficiency



Why develop automotive TEG's?

- **Improve vehicle fuel efficiency**
  - Customer driven requirement
  - Government driven requirements
- **Requirements to lower CO_2 emissions**
- **Green image to help vehicle sales**
- **Support increased vehicle electrification**
- **Simpler than alternative systems:**
  - Rankine, Stirling, thermo-acoustic, etc.

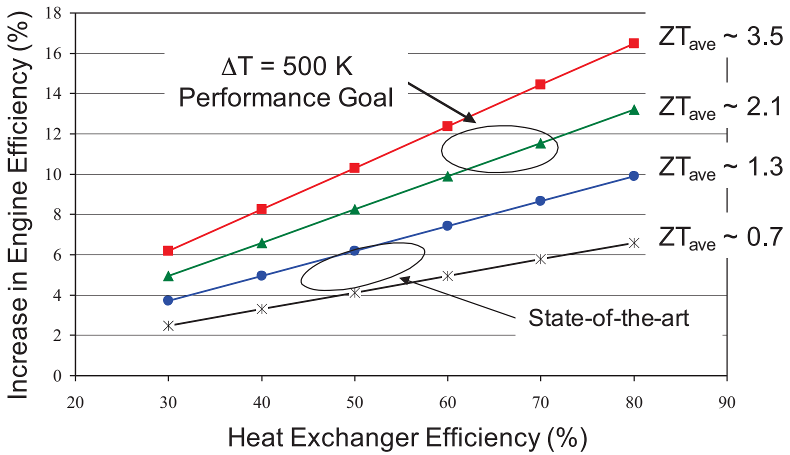
Heat Distribution in Vehicles



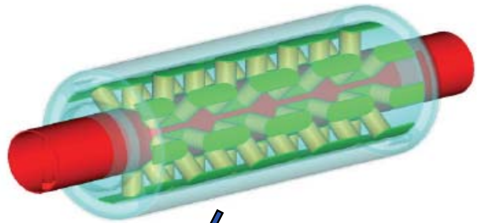
Exhaust is the most promising waste heat source

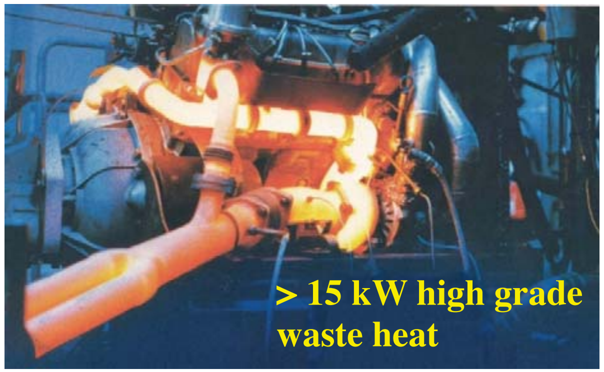
TE for Vehicle Waste Heat Recovery

- **Thermoelectrics in Vehicles**
  - **TE has unique advantages for integration**
- **What has been done?**
  - **Low efficiency Bi_2Te_3-based TE generators (TEG) demonstrations**
- **What is needed?**
  - **Increase TEG operating temperatures, ΔT**
  - **Integrate abundant, low-toxicity, higher ZT materials (ZT_{ave} ~ 1.5 to 2)**
  - **Develop and scale up HT TE module technology**
  - **Integrate with efficient heat exchangers**

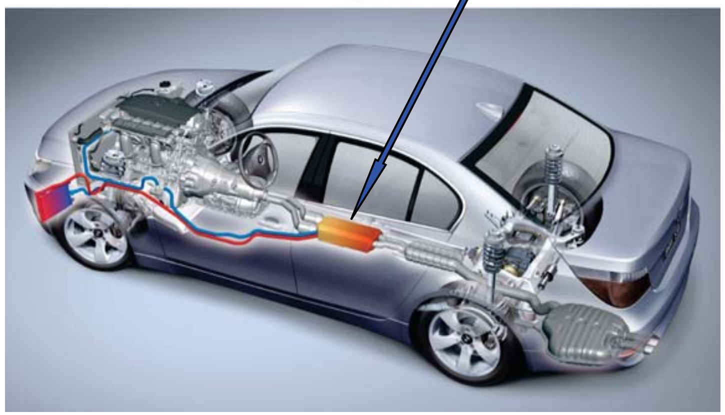


Exhaust Pipe TE Electrical power generator





> 10% Fuel Efficiency improvement with exhaust waste heat recovery



What are the major components of a thermoelectric generator (TEG) system?

- **TEG Unit**
  - Hot side heat exchanger & flow controls
  - Cold side heat exchanger and flow controls
  - Thermoelectric modules
  - Enclosure
- **Hoses, pipes, flow management**
- **Thermal management components (optional)**
- **Vehicle mechanical interface - mounting**
- **DC to DC converter & electrical interface**

BSST TEG mounted in BMW

Slide courtesy of General Motors Corp.

TEG Installation in GM Suburban

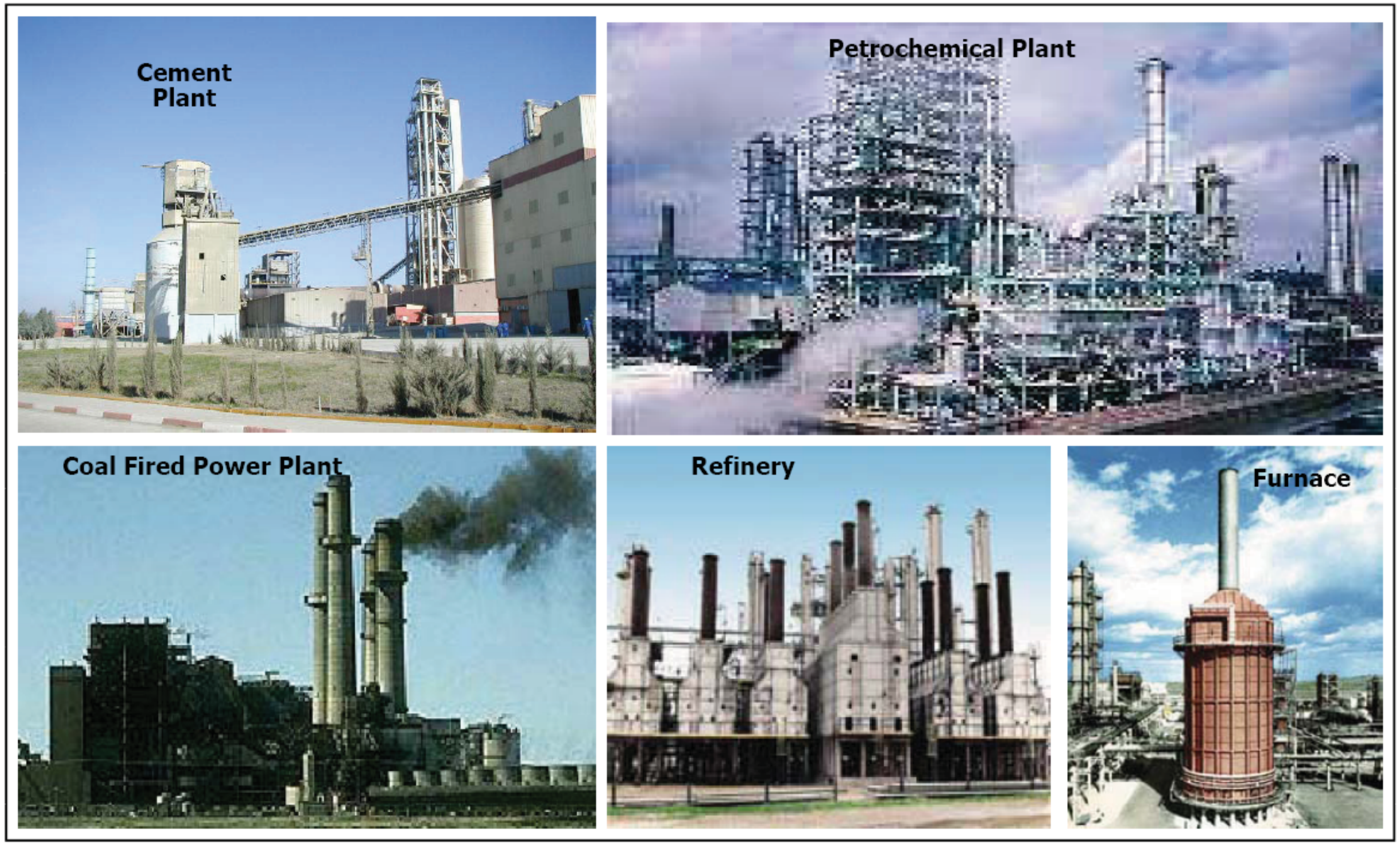
Economic Considerations

- **The real number to focus on is $ per MPG (miles per gallon) improvement**
  - May use $ cost per Watt output for the complete TEG system
  - ~ $1/W cost target

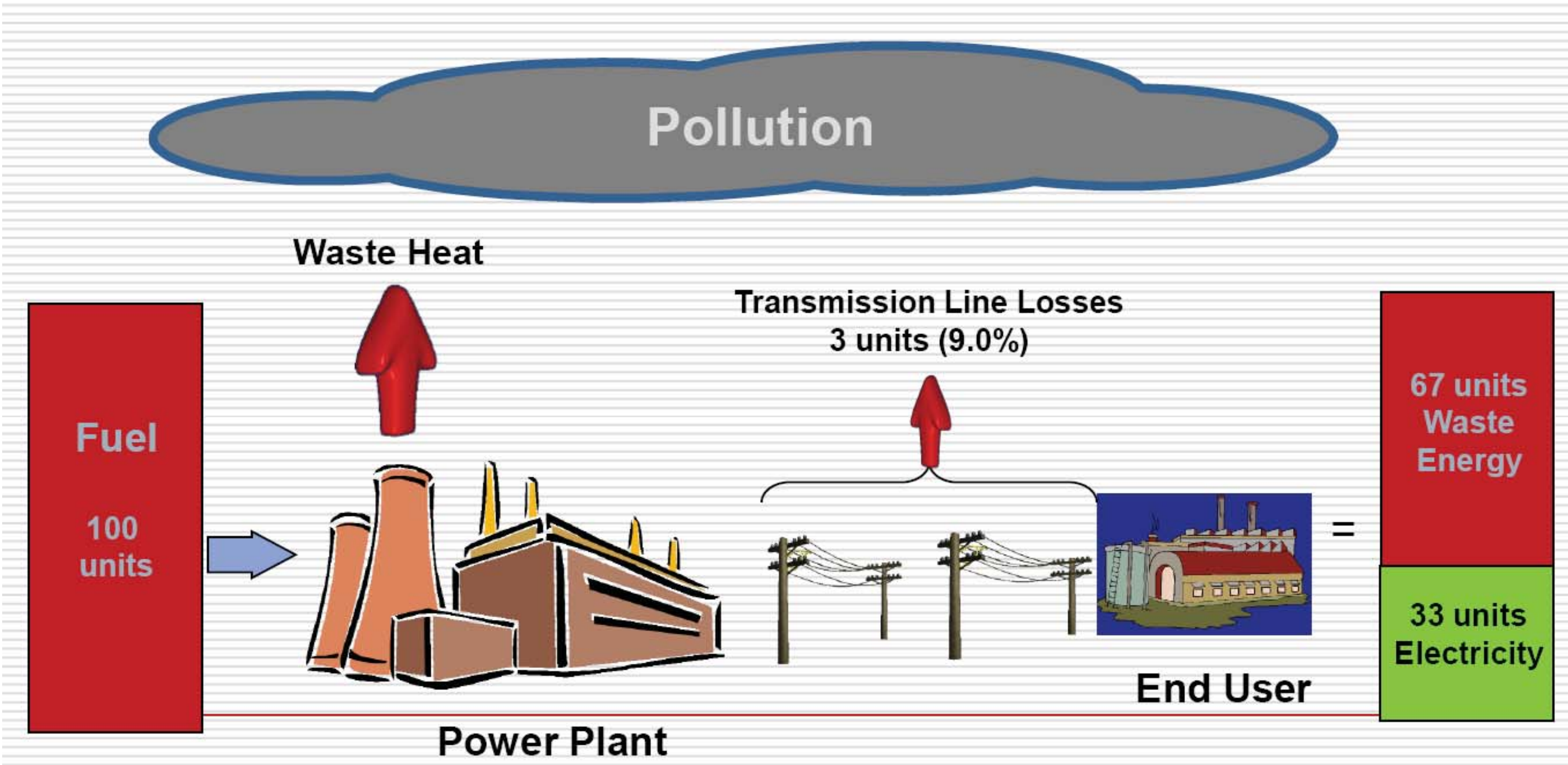
- **The customer must perceive sufficient benefit to pay for the cost of a TEG**

- **Some of the benefit may be "Green Image" but most of the benefit has to translate into fuel savings**
  - Eliminating the use of the conventional generator for a vehicle on a US Government fuel economy test (FTP) will save 1.5 to 3.0% fuel economy depending on the type of vehicle
  - Real world driving may provide additional fuel savings

Waste Heat Sources

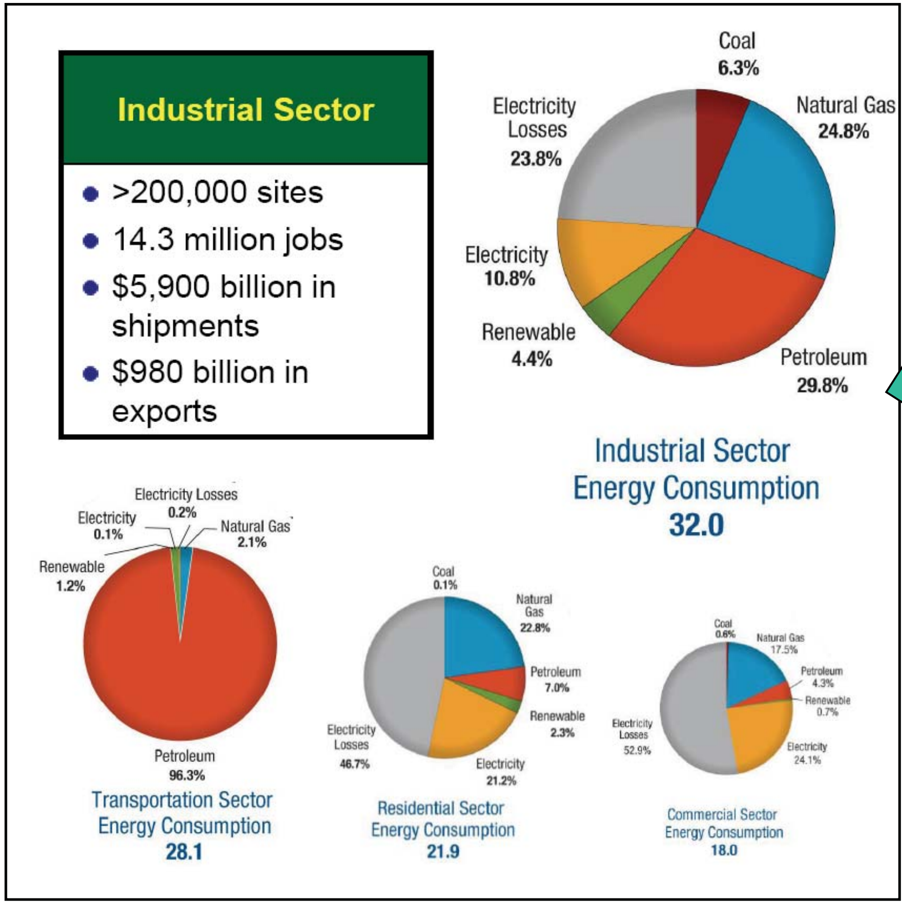


Average Power Plant Generation Efficiency



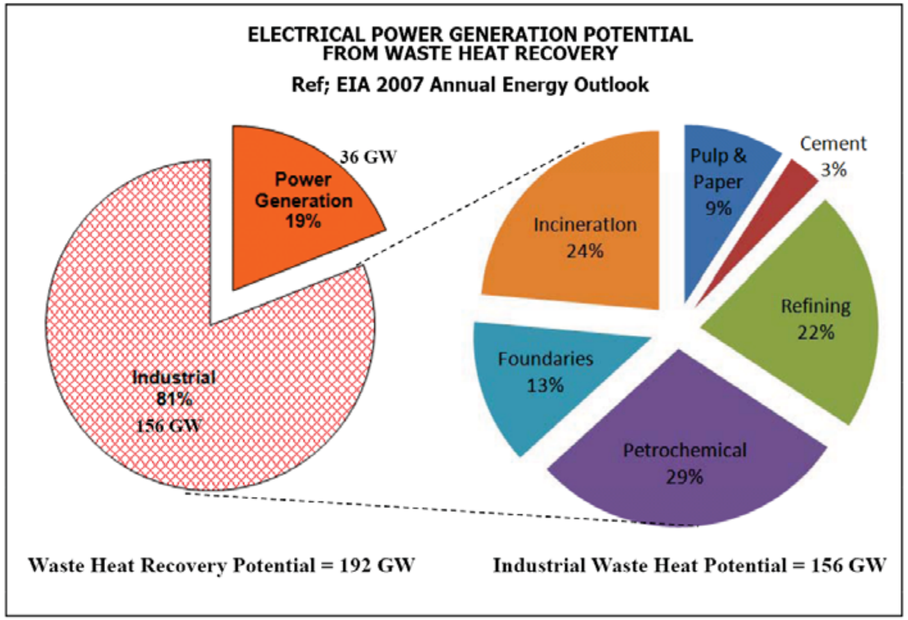
- **Efficiency has not improved significantly in last 40 years for large scale power plants**

Opportunities for Power Generation by Recovering Waste Heat



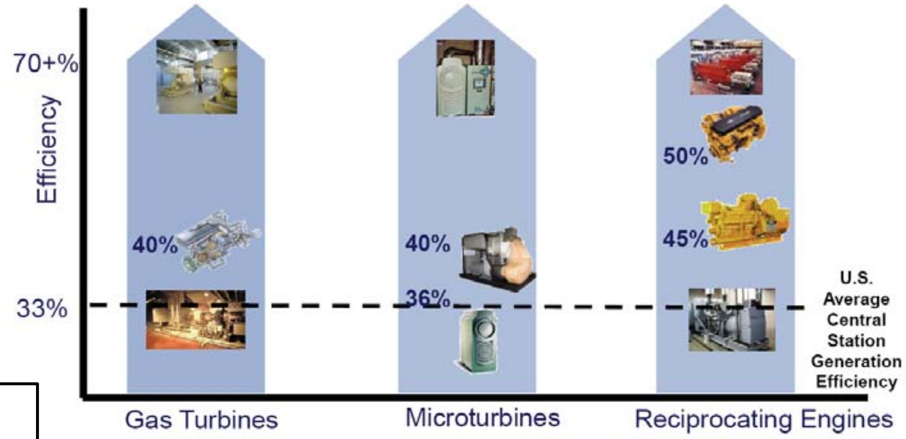
* USA data

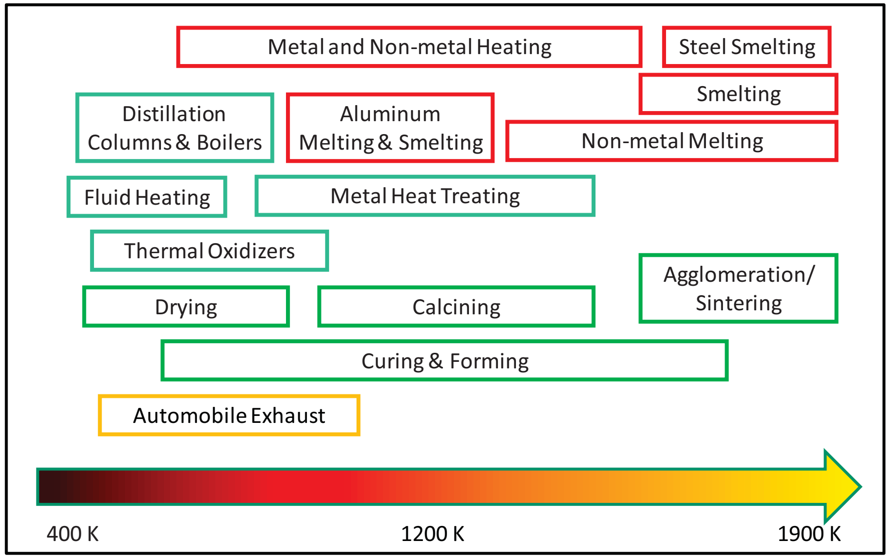
Wide range of heat source types and temperatures from energy intensive industrial processes



Dynamic Power Systems Are Efficient

- **Thermoelectrics cannot compete "head-on" with dynamic technologies**





Adapted from: Hendricks, T., Choate, W. T., Industrial Technologies Program, "Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery" (U.S. Department of Energy, 1-76, 2006).

- Some industrial processes are potentially attractive for TE systems
  - Medium to high grade heat Medium to high grade heat for aluminum, glass, metal casting, non-metal melting, ceramic sintering and steel manufacturing
  - Limited opportunity to reuse the waste heat
  - Difficulties in effectively transporting that heat to separate energy conversion systems

Major Opportunities in Manufacturing & Energy Industries

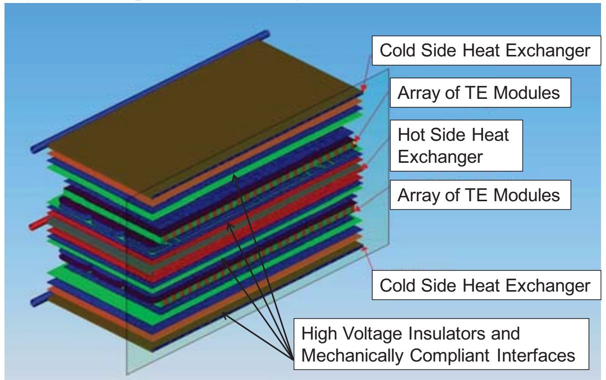
- **Large scale waste heat recovery of industrial and power generation processes**
  - Benefit from higher energy costs and reduction of fossil fuel pollution to retrofit existing facilities
  - High grade waste heat sources from a variety of industrial manufacturing processes
    - For near term applications in the US alone, between 0.9 and 2.8 TWh of electricity might be produced each year for materials with average ZT values ranging from 1 to 2
  - Efficient heat exchangers, large scale production of TE materials and modules are required
    - Also need to focus on economical, low toxicity materials

		T_{source} (K)	Available Waste Heat GWh/year	TEG Recoverable Waste Heat GWh/year		
				ZT=1	ZT=2	ZT=4
Applications Set A: low hot-side temperature, relatively clean flue gas						
Commercial	Water/Steam Boilers	425	164,010	n/a	n/a	n/a
Industrial	Water/Steam Boilers	425	178,654	n/a	n/a	n/a
	Ethylene Furnace	425	8,786	n/a	n/a	n/a
Applications Set B: medium hot-side temperature, mixed flue gas quality						
	Aluminum Smelting	1230	1,230	59	176	293
	Aluminum Melting	1025	8,376	410	1,259	2,109
	Metal Casting Iron Cupola	650				
	Steel Blast Furnace					
	Lime Kiln					
	Cement Kiln (with pre-heater)	475	2,050	88	293	498
Applications Set A: High hot-side temperature, mixed flue gas quality						
	Cement Kiln (no pre-heater)	1000	2,460	117	381	615
	Glass Oxy-fuel Furnace	1700	1,406	59	205	351
	Glass Regenerative	750	3,456	176	527	879
	Total		**370,428**	**908**	**2,841**	**4,745**

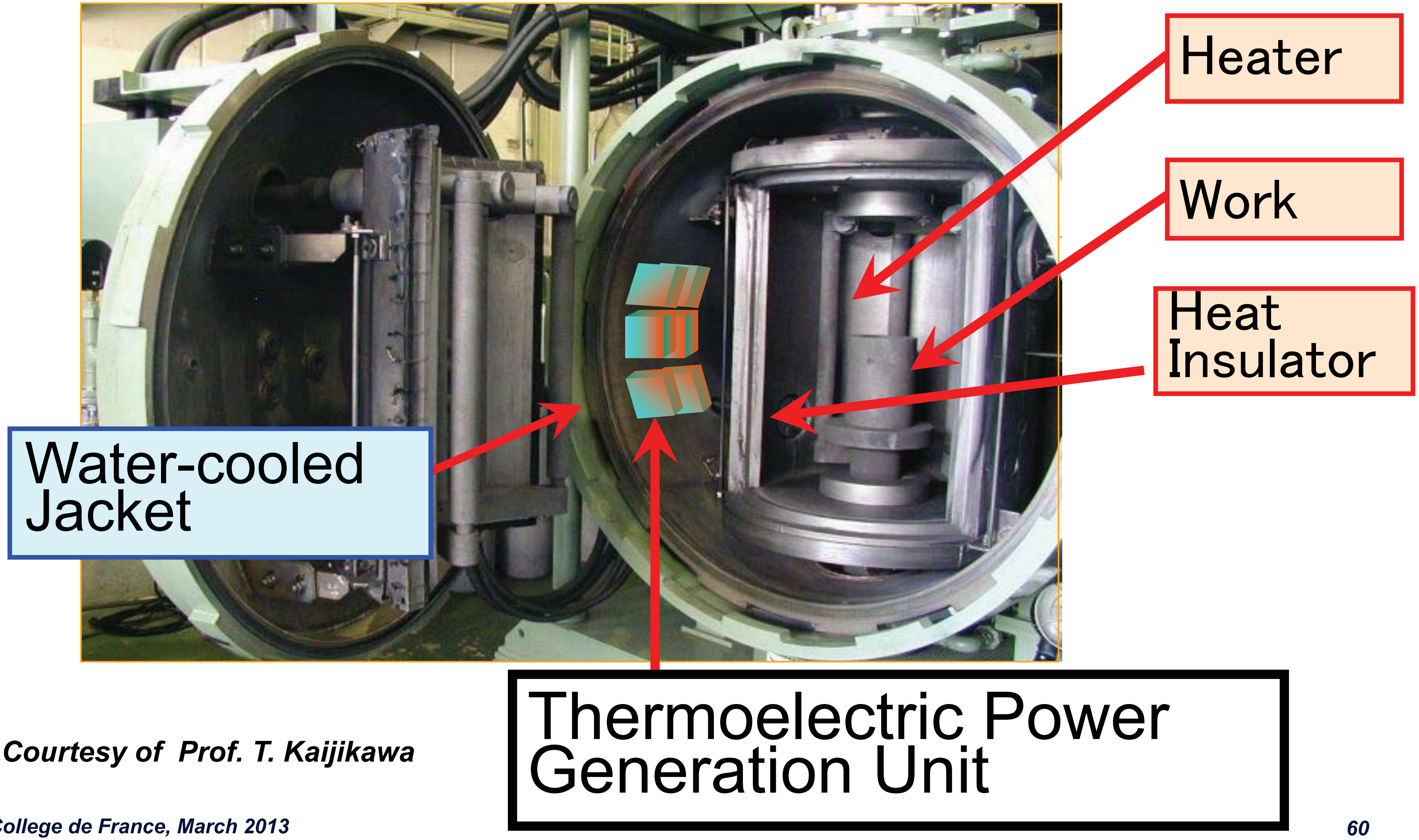
Adapted from: Hendricks, T., Choate, W. T., Industrial Technologies Program, "Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery" (U.S. Department of Energy, 1-76, 2006).

Potential High Temperature Thermoelectric Waste Heat Recovery System

(concept developed for 100 kW-class thermoelectric generators operating up to 1275 K)

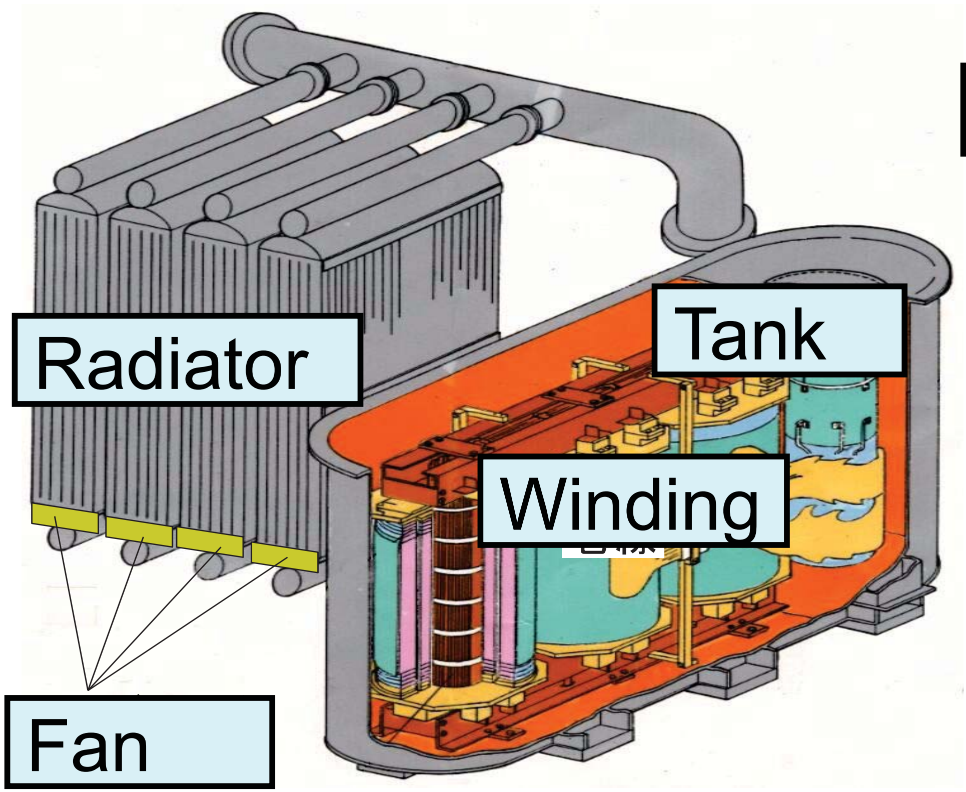


Thermoelectric Power Generation System for Industrial Electric Heating Furnace

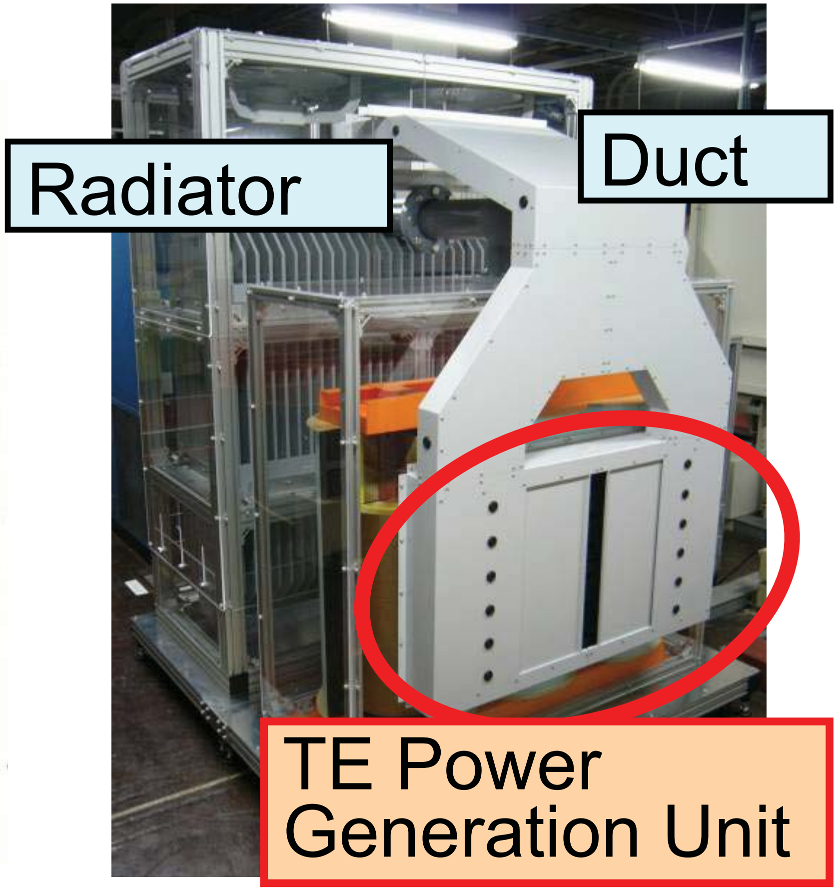


Courtesy of Prof. T. Kaijikawa

Thermoelectric Power Generation System using rejected heat from Electric Transformer



Schematic of Electric Transformer



Demonstrated system

Courtesy of Prof. T. Kaijikawa

Summary

- **To date, thermoelectrics has been mostly applied for niche markets**
  - Using TE materials developed in the 60's

- **New development in TE materials may open up new markets**
  - Automobile, industrial processes waste heat recovery

- **Both low cost and smart system engineering are needed to make these applications viable**

- **ZT ~ 3 cooling materials would open larger markets**