Thermoelectric Energy Conversion

Future Directions & Technology Development Needs

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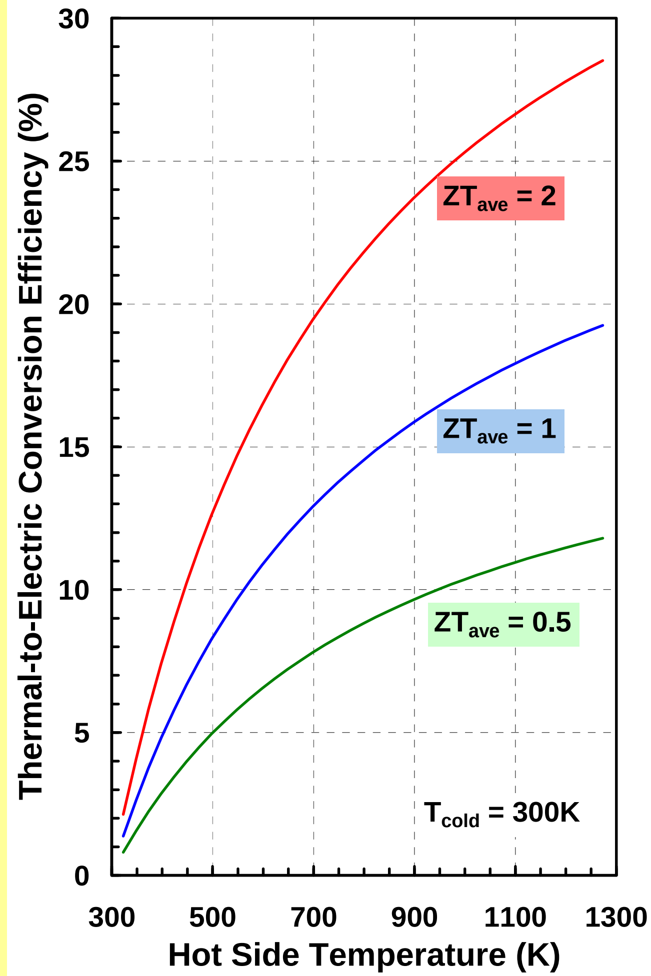
The Case For Thermoelectrics (TE)

- Current TE conversion efficiency usually too low to compete with dynamic technologies for stand-alone systems
  - Current TE materials:
    - Power: 8 to 15% against 25 to 45%
    - Cooling: COP is 3x lower than typical compressor
  - Advanced TE materials goals in the next 3-5 years:
    - Power: 20-30% efficiency (*average ZT of 2.0*)
    - Cooling: 2x to 5x increase in COP, 100x power density
- But TE technology has highly valuable attributes
  - Solid-state, highly scalable and modular
    - No moving parts, no vibrations, silent operation
    - Can outperform competition for small scale applications
  - High level of reliability and redundancy
    - Proven record of long life space and terrestrial applications
- Attractive for a number of applications
  - Small scale stand-alone power and cooling systems
  - Within integrated systems
    - Both large scale systems & miniaturized devices
    - Such as waste heat recovery, localized thermal management

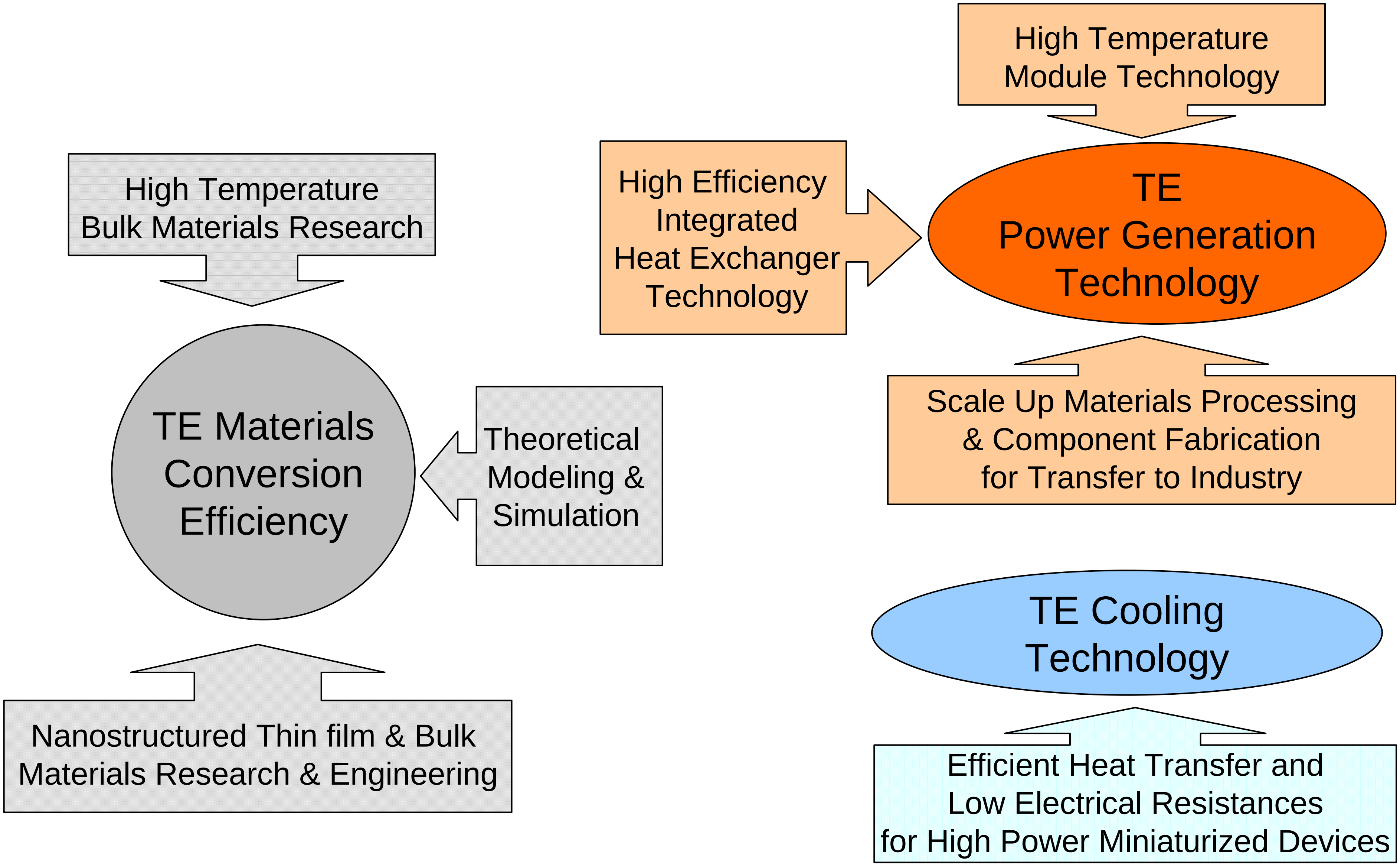


Power generation

State-Of-Practice materials: $ZT_{average}$ ~ 0.5
State-Of-the-Art materials: $ZT_{average}$ ~ 0.9
Best SOA materials: ZT_{peak} ~ 1.5 to 2.0

Advances in Thermoelectrics: Investment Needed

TE Research & Technology

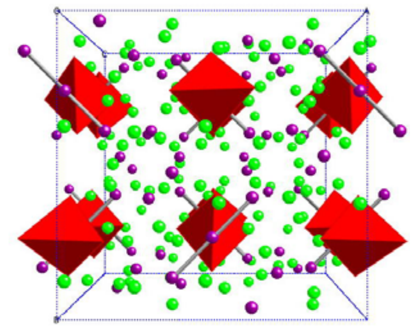


Current U.S. Investment (FY07)

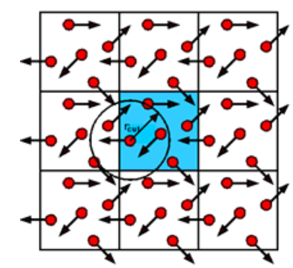
	High Efficiency Materials	TE Power Generation Technology	TE Cooling Technology
High Temperature TE Materials	• NASA • ONR (MURI)		
Nanostructured Thin films R&D	• ONR (MURI) for cooling		
Nanostructured Bulk Materials R&D	• NASA • ONR, DOE		
Theoretical Modeling & Simulation	• NASA • ONR		
High Temperature Couple Technology		• NASA (Adv. RPS), 1300 K hot side • DARPA (DTEC), 900 K hot side • DOE (automobile), 700 K hot side	
High Temperature Module Technology			
Scale up of materials and components			
High temperature heat exchanger		• DOE (automobile)	
High power microcoolers			• ONR, Industry

Increasing Thermoelectric Materials Conversion Efficiency
Key Science Needs and Challenges

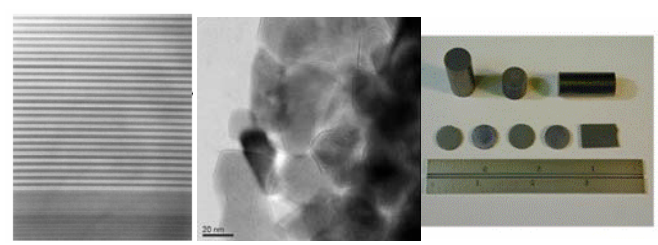
- Identification, synthesis and characterization of complex bulk materials with good potential for high efficiency
  - Large phase space, especially for lower temperature applications
  - Reproducible synthesis with controlled stoichiometry, defect concentration and dopant concentrations
- Need for theoretical modeling and simulation of transport in “real”, practical materials
  - Predictions are very encouraging but often apply to “ideal” geometries
  - Large ZT values projected for feature sizes < 10-30 nm
    - Perfect superlattices and wires
- Controlled engineering of “nanostructured” materials
  - Thin films: superlattices and quantum well structures
    - Easier to control synthesis and structure but more difficult to characterize due to low dimensionality
  - “Nano Bulk”: nanoparticles, nanoclusters, texturing…
    - Much more difficult to control synthesis, homogeneity and orientation but potentially eliminate transport property measurement issues
- Need for reliable transport property measurements
  - In particular at high temperatures and for low dimensional structures
  - Independent validation is a must



Advanced Complex Structure Materials



Theoretical Modeling and Simulation of Thermoelectric Transport

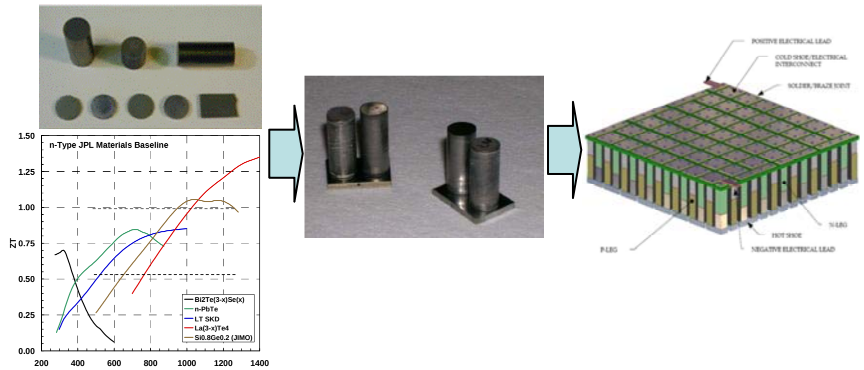


Engineered Nanostructured Thin Films and Bulk Materials

Developing Advanced TE Components & Systems
Key Technology Needs and Challenges

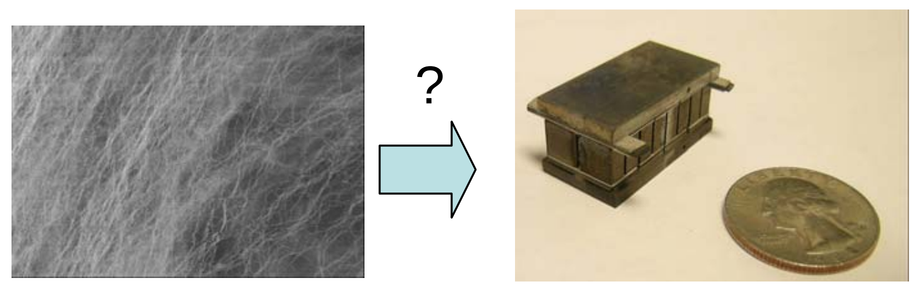
TE Research & Technology

- Develop component technologies based on new advanced bulk materials
  - Several classes of high ZT materials now available
  - Power generation application needs modular, off-the-shelf technology capable of handling:
    - High operating temperatures (900 K to 1300 K)
    - Thermal cycling (terrestrial applications)
    - Long life operation (years)



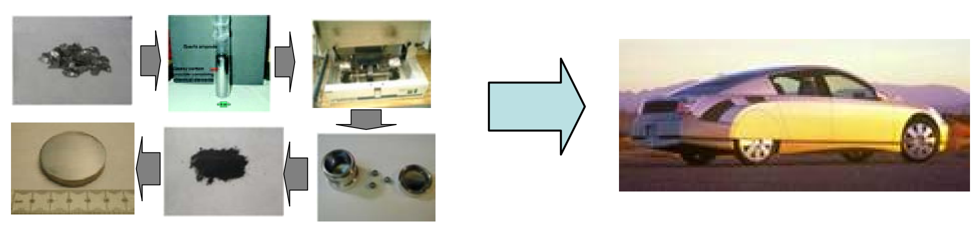
Integrate new high ZT materials to high efficiency high temperature modular technology

- Realize potential of micro/nano technologies
  - High ZT (x2 to x3 higher than SOA) reported
  - But not fully demonstrated at the device level
    - High power density = high heat fluxes
      - Thermal & electrical contact resistances issues
      - Nanostructure stability, thermal & mechanical device integrity issues



From nanostructures to practical devices

- Overcome large scale application challenges
  - Low cost processes are needed
    - Material production and processing: kg vs. mg
    - Powder metallurgy, chemical synthesis, electrochemistry,...
  - Processing/operation compatibility within integrated systems



Industrial processing/manufacturing for large scale applications

Thermoelectrics

Application Opportunities That Would Require Developing Advanced Technology Based on Existing State-of-the-Art Materials

200W Class Lightweight Portable Thermoelectric Generator

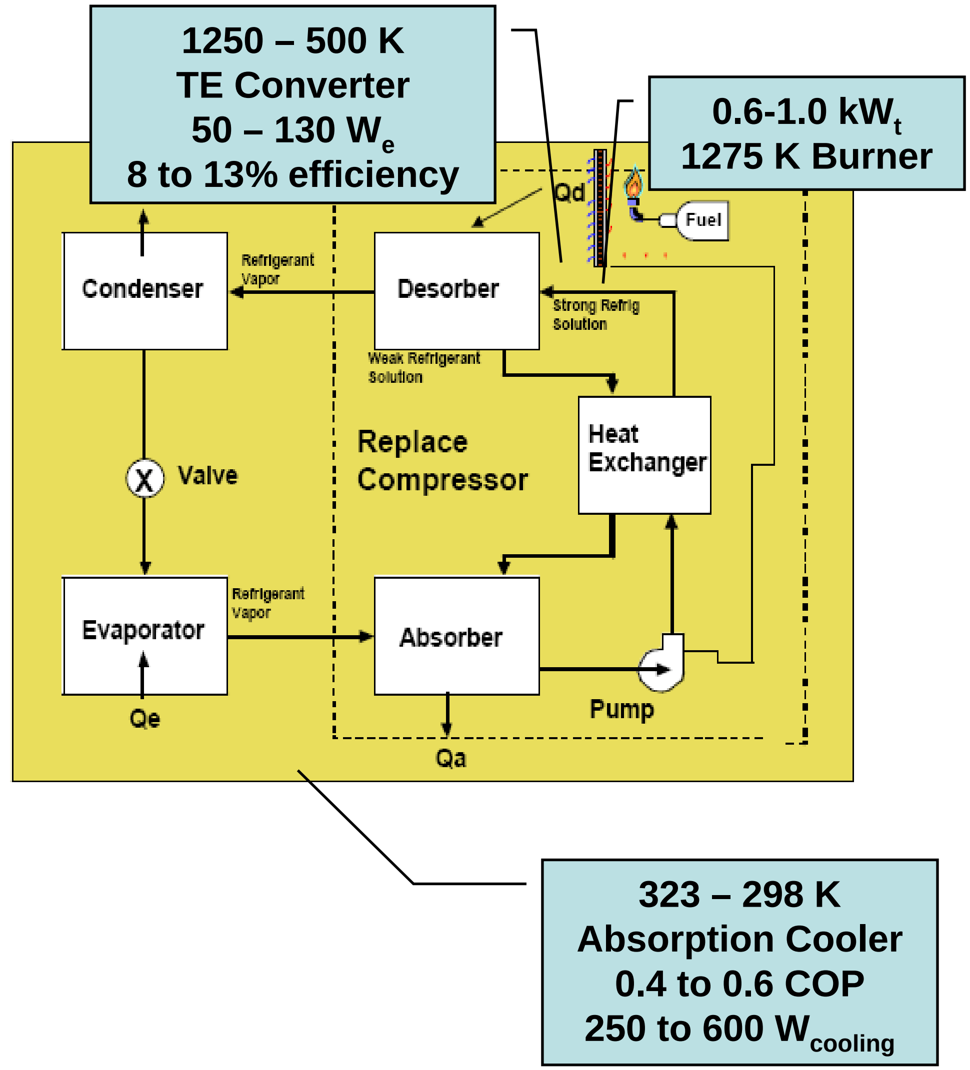
- Army needs portable 100-200 W class generators
  - Army's smallest units are currently in the 2 to 3 kW range (diesel generators)
- TE technology developed in early 1980s (100-600W range) had low overall fuel-to-electric efficiency (~ 2.6%) but many attractive features
  - Fuel flexible operation (such as JP-8)
  - High level of converter redundancy and reliability, easily scalable
  - Rugged, low noise, low IR signature, and low maintenance requirements
- ½ the weight, x 2 the electrical power now possible over existing proven thermoelectric generator technology
  - Only limited design and configuration changes
  - Combining proven TE technology and power systems heritage with new advances in components

Power Inventory		Baseline TEG MEL 120 W (W)	Advanced TEG MEL 200 W
Ancillaries	Blower (including ECA control)	11.0	4.88
	Atomizer	7.2	
	Cooling fan	13.0	8.3
	Fuel pump (includes fuel solenoid)	1.0	2.05
	Ignitor (steady state contribution)	0.2	
	Battery charge	4.7	
		37.1	**15.2**
Electronic Control Assembly (ECA)	Shunt Regulator driver	0.3	
	Load switch relay	2.4	3.9
	Microprocessor	2.0	
	Internal wiring and diode Joule losses	2.4	12.8
		7.1	**16.7**
Other:	Main Harness Joule Losses	0.7	
	DC/DC Converter (85% and 90% eff.)	21.2	22.2
	Shunt regulator reserve	2.0	
	Output component loss	3.1	2.7
		27.0	**24.9**
Load:		**120.0**	**200.0**
Gross TEG Output		**191.2**	**256.8**

- 200 W class advanced MITG
  - JP-8 operated, 12 hour continuous power autonomy, 24 VDC output
  - Parametric study results based on state-of-practice (SOP) TE generator designs and mass equipment lists
  - 1175 K/ 400 K hot and cold junction temperatures for TE converter
  - Projecting 10 kg wet system mass, 20 W/kg specific power (including fuel)

Hybrid Absorption Cooling/TE Power Cogeneration System

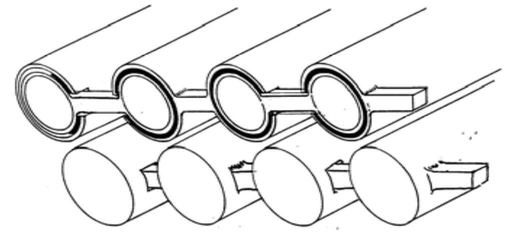
- Waste heat recovery of high efficiency combuster heat used for high efficiency absorption cooler
- Rejected heat transferred to desorber
- TE converter operates between combuster and desorber temperatures (1275 K and 450 K)
- TE converter covers parasitic power load (10% of cooling load) and extra power generated provided for auxiliary electronics (25 to 50 W)
- Concept extensible to larger systems



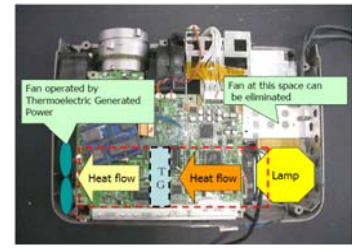
Major Opportunities in Energy Industry

TE Research & Technology

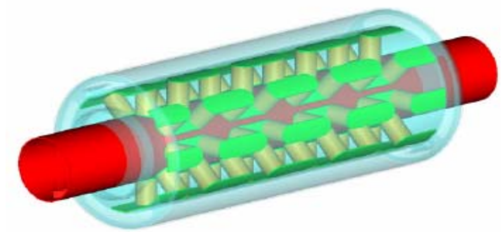
- Large scale waste heat recovery of industrial processes
  - Benefit from higher energy costs and reduction of fossil fuel pollution
    - Japan's NEDO projects has a 2010 goal of producing 213 GWh of electrical power
      - Using TE power generation systems
      - Reduces CO_2 emissions by 73000 tons
    - Power plant bottoming cycle to support peak energy summer demands and avoid building of new plants
      - Higher ZT = lower cost
      - 1998 study: 3x ZT = ½ material cost
- Hybrid low cost power sources
  - Flexible solar cell/thermoelectric/battery hybrids
    - Day & night operation, easy deployment



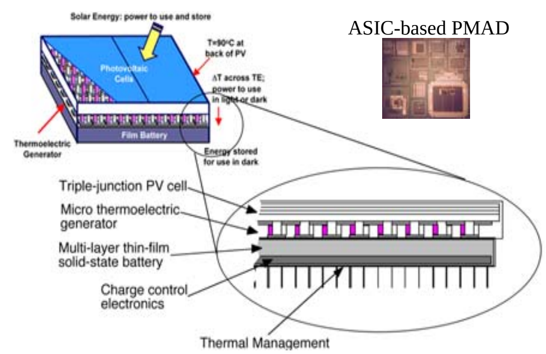
Paired Tube TE Hot Industrial Water-Water HX



Power Electronics Thermal Management

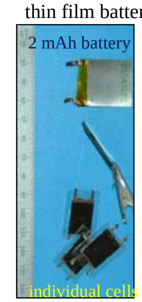


Automobile Exhaust Waste Heat Recovery



ASIC-based PMAD

Solid-state, multi-layer thin film battery

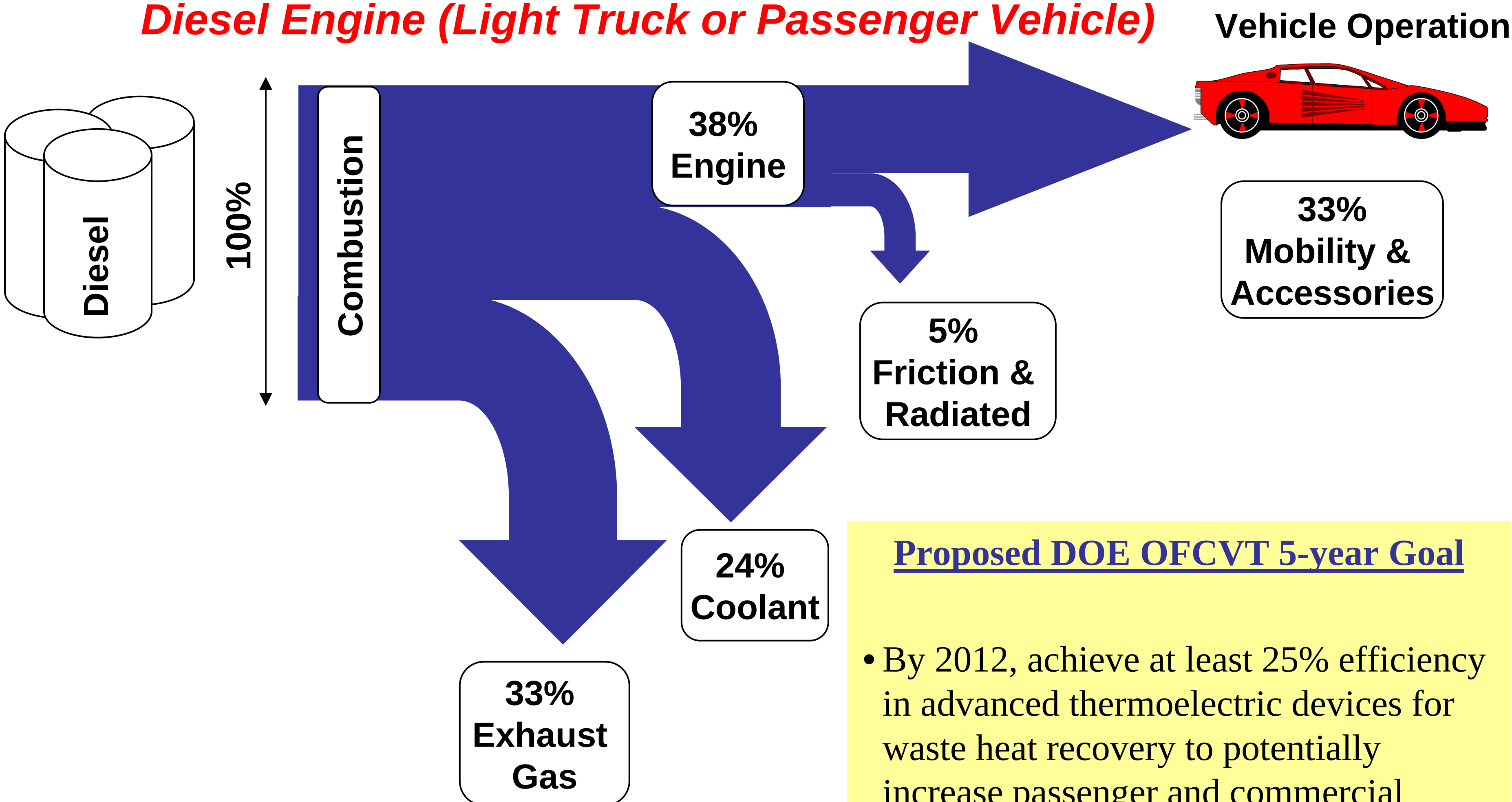


COTS device that was tested

Hybrid "Power Tile" Concept

Automobile Waste Heat Recovery

Diesel Engine (Light Truck or Passenger Vehicle)



Proposed DOE OFCVT 5-year Goal

- By 2012, achieve at least 25% efficiency in advanced thermoelectric devices for waste heat recovery to potentially increase passenger and commercial vehicle fuel economy by 10%.

Thermoelectrics at JPL

Thermoelectrics at JPL

TE Research & Technology

Expertise

- 35 years of materials research, component development and testing for radioisotope power sources
- More than twenty years of program management, R&D experience in reactor power sources
- More than thirty years of mission requirements analysis and project support/engineering

Technologies

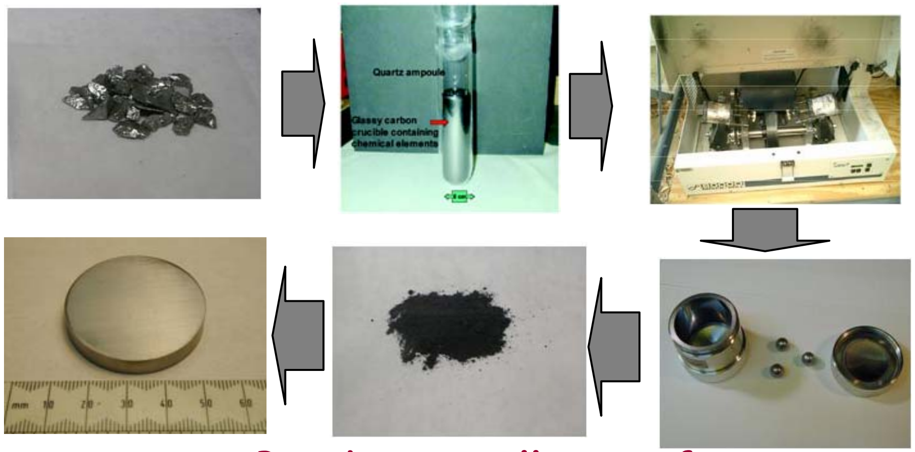
- Advanced high temperature materials
- Segmented thermoelectric couples
- Advanced lightweight thermal insulation
- Micro/nanoscale generator & coolers
- Performance modeling tools
- Materials modeling tools
- Space Power System Design & Engineering

Facilities

- Thermoelectric Materials
  - Bulk synthesis & powder metallurgy processing
    - 10s to 100s of g batches
  - Hot-pressing (uniaxial/HIP)
  - Thermal & Electrical Transport Property Measurements
    - From 4 K to1300 K
  - Thermal stability characterization
    - TGA/DTA/DSC, dilatometer
- Thermoelectric Devices
  - High temperature bonding/brazing
    - TE leg metallizations
    - Unicouple/multicouple assembly
  - Performance and life testing
    - Vacuum or inert atmosphere

Recent Advances at JPL in Thermoelectric Converter Component Technologies

TE Research & Technology

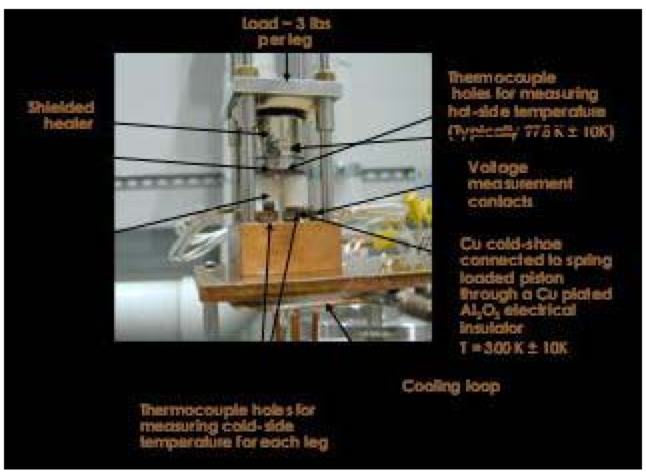


Powder metallurgy of Advanced TE materials & elements

Skutterudite unicouple with Nb hot-shoe

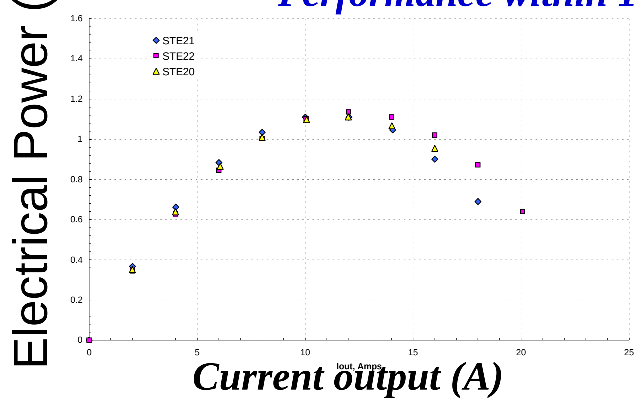
2x4 couple Skutterudite Module

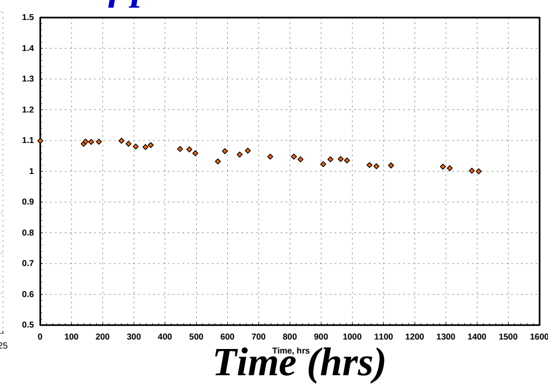
Fabrication & Assembly of High Performance Thermoelectric Power Generation Devices



975 -300K 14% conversion efficiency demonstrated

Performance within 1-3% of predictions





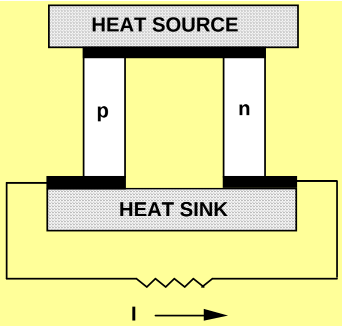
Thermal packaging, performance and life testing of High Temperature, High Performance Thermoelectric Power Generation Devices

Thermoelectrics

Background on Power Generation and Cooling Operational Modes

Thermoelectric Power Generation

TE Research & Technology



Power generation

$Z = \frac{\alpha^2}{\rho\lambda}$

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

Large ZT values are needed to achieve high conversion efficiency

Conversion Efficiency

Carnot — TE Materials

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

Converter Design & Operation

Heat Source → $Q_{in} = K_{TE} . \Delta T$ → Converter Efficiency

TE Materials
Single stage, segmented, cascaded

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

Radiator for Heat Rejection

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

Radiative or Conductive Coupling → Converter Configuration (A/l aspect ratio)

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

TE couples in series/parallel

Total Number of TE couples → Unicouples or Multicouples Arrays

Converter Voltage Output

$V_{OC\ converter} = (N_{couple} / N_{parallel\ strings}) S_{pn} \Delta T$

Best experimentally demonstrated maximum ZT values ~ 1.5 to 2.0

Thermoelectric Cooling

- Two important design conditions
  - Maximum cooling power ($\Delta T=0$)
  - Maximum cooling temperature ($P=0$)
- Both conditions directly proportional to ZT
- Projected COP for temperatures of interest in soldier cooling applications
  - 297 K at 323 K ambient
  - State-of-practice: ZT ~ 0.7
    - Bulk and thin film devices
    - ZT ~ 2.0 reported on thin film superlattices but no validation
      at the device level yet

$$COP_{\max} = \frac{Q_{\max}}{P_{\max}} = \frac{T_{cold}}{T_{hot} - T_{cold}} \frac{\sqrt{1+ZT} - \frac{T_{hot}}{T_{cold}}}{\sqrt{1+ZT} + 1}$$

$$\Delta T_{\max} = \frac{ZT_{cold}^2}{2}$$