Thermoelectrics and Waste Heat Recovery

Lon Bell, Ph.D.

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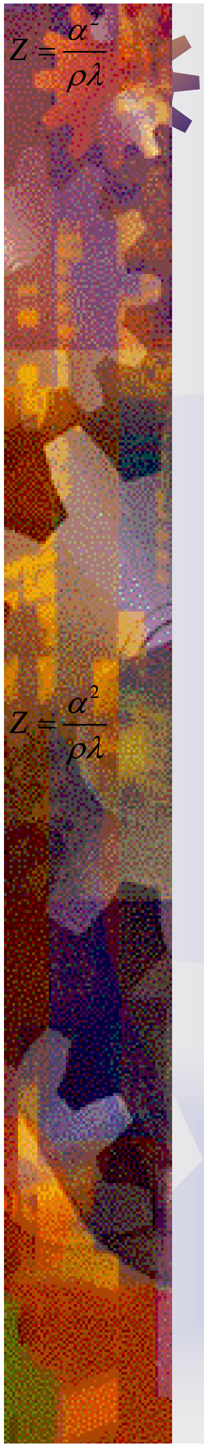
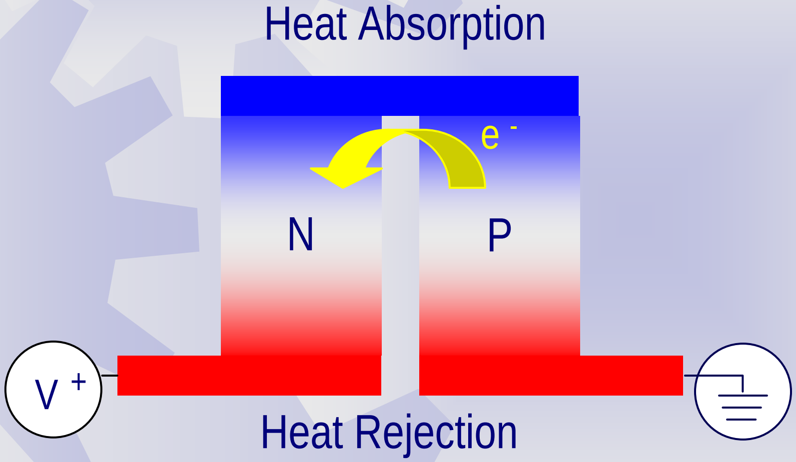
BSST
innovative solutions
in temperature control



Thermoelectric Heat Engines

Cooling / Heating

(Peltier Effect)


Heat Absorption

e -

N

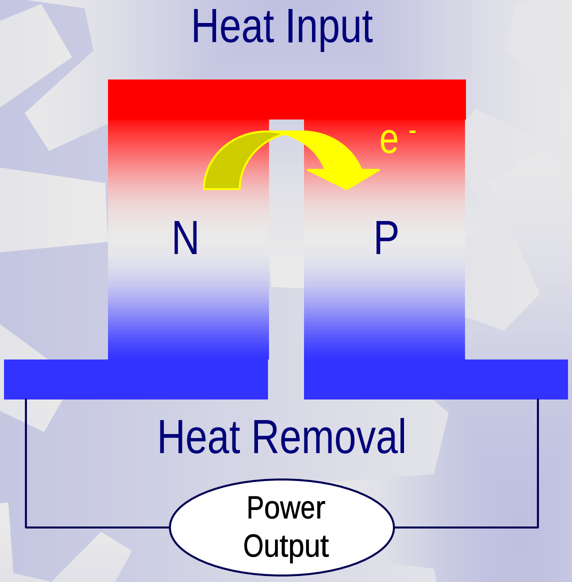
P

V +

Heat Rejection

Power Generation

(Seebeck Effect)


Heat Input

e -

N

P

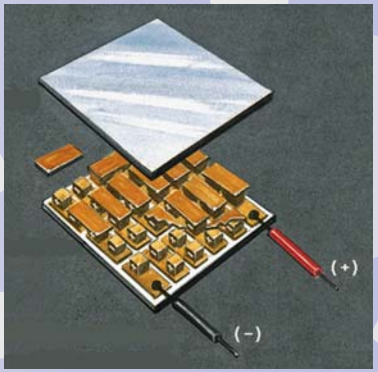
Heat Removal

Power Output

Traditional

Module

Configuration



TE Figure of Merit

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

α - Seebeck Coefficient
ρ - Electrical Resistivity
λ - Thermal Conductivity

Why Use Thermoelectrics?

Solid-state cooling, heating and power generation

Small, light-weight. Potentially very reliable and rugged

Electrically powered with very few (or no) moving parts

Distributed (and spot) cooling/heating/temperature control

No gaseous pollutants/CO_2 replacement

What Has Limited Usage?

Cooling efficiency has been less than 12% and power generation less than 16% of Carnot

- Inadequate for many high-power applications
- Limits usage to small applications
- Too inefficient for auxiliary power generation and general cooling and heating

Thermal flux density has been low

- Volume and weight too great at high power levels
- Form factor not readily adaptable to some application needs
- Poor interface to high-power density applications

Lack of design knowledge and effective simulation tools

- Performance often poorer than predicted
- Characteristics and, hence response, can be a strong function of operating conditions

TE System Performance Gains

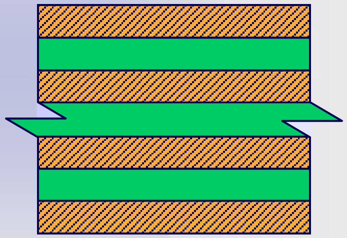
Materials	
BiTe Thermoelectrics (1960s)	Baseline
Heterostructures (2000-2002)	+70 to 160%
Materials/Design	
Incremental improvements (1960-2002)	5 to 15%
New ancillary materials and components (1960-2002)	5 to 10%
Thermodynamic Cycle	
Isolated Element (2000-2002)	100 to 120%
Convection (2001-2002)	30 to 80%
Power Density	
Sintered micropower (2002)	Up to 25 X Increase
Heterostructure (2001)	30 to 300 X Increase

Material Advancements

RTI (2001)[1]

- Electron Passing / Phonon Blocking
- Nanoscale Heterostructure
- 0 - 250°C Operation

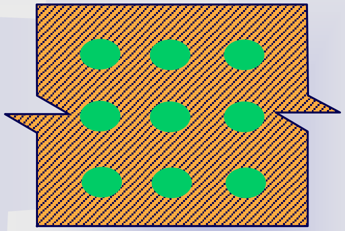
[1] Venkatasubramanian, R. *et al*, "Thin-Film Thermoelectric Devices With High Room-Temperature Figures Of Merit," *Nature*, Vol. 413, (2001), pp. 597-602.



Lincoln Laboratory (2002)[2]

- Quantum DOT Super Lattice
- Cross Plane and In Plane Usage
- 0 – 300+°C Operation

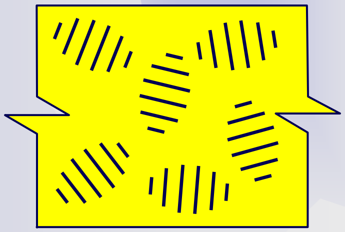
[2] Harman, T.C., "Quantum Dot Superlattice Thermoelectric Materials and Devices," *Science* Vol. 297 (27 September 2002), pp. 2229-2232.



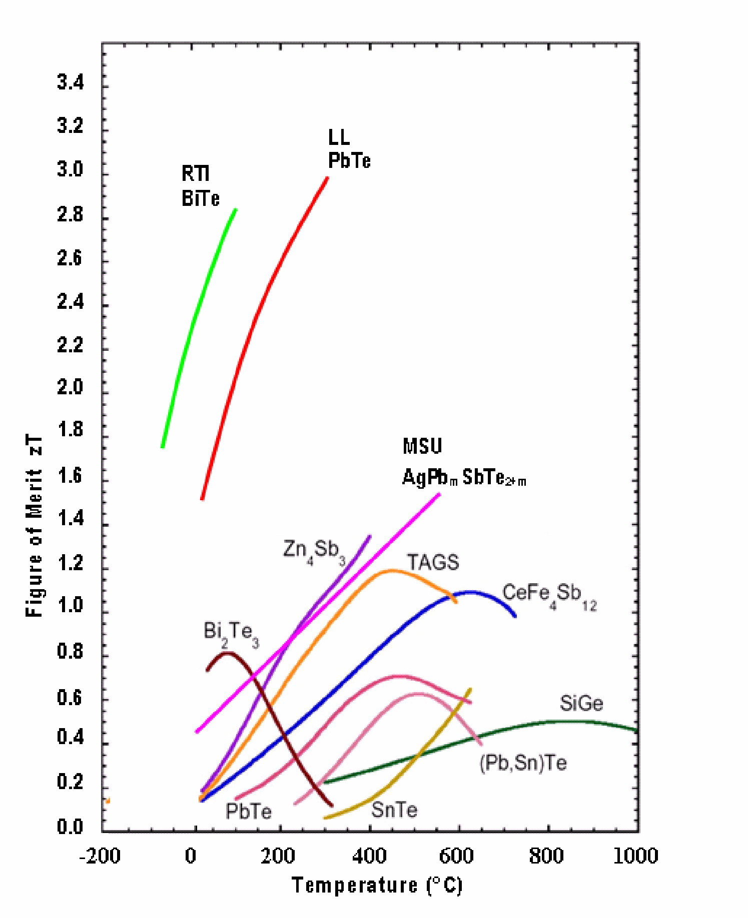
Michigan State University (2003)[3]

- Complex Crystaline Bulk Material
- Indications of Imbedded Coherent Nanostructures
- 150°C – 500°C Operation

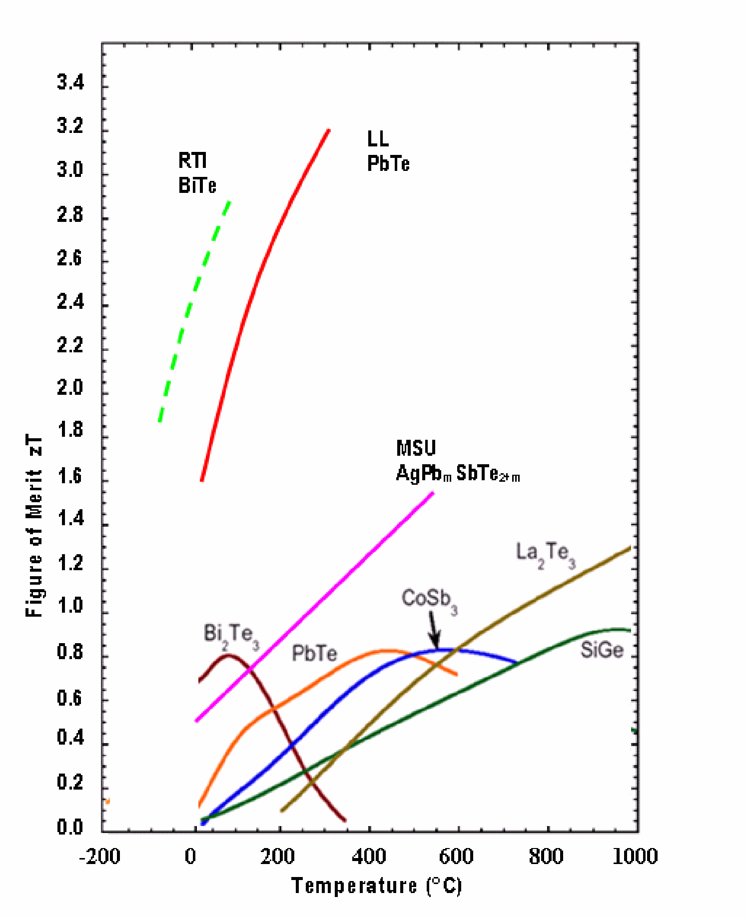
[3] Mercouri G. Kanatzidis, et. al., *2007 Direct Energy Conversion Review and Workshop*



Lincoln Laboratory (LL), and Michigan State (MSU), and RTI Have Exhibited Important Gains



P-type

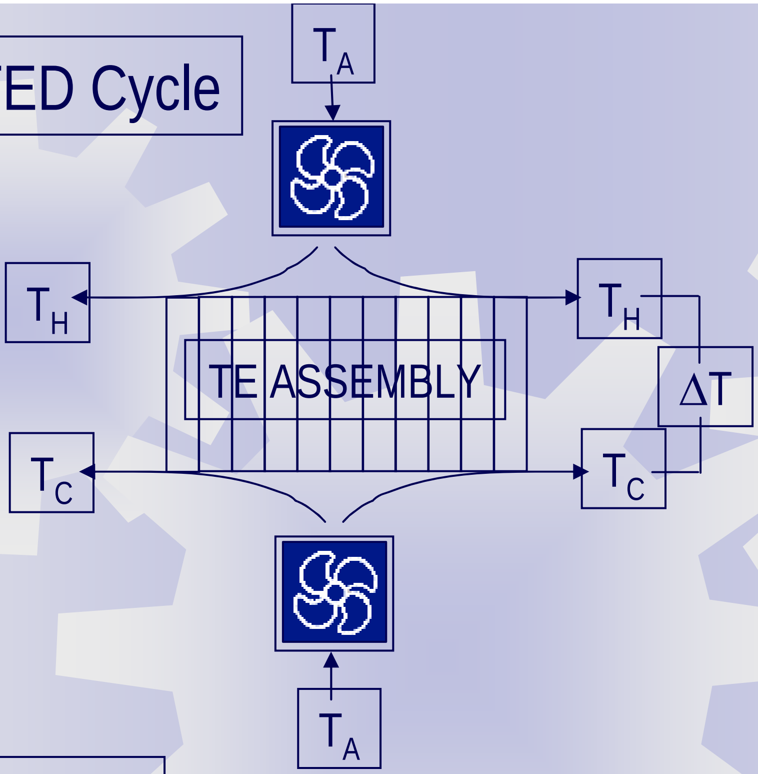


N-type

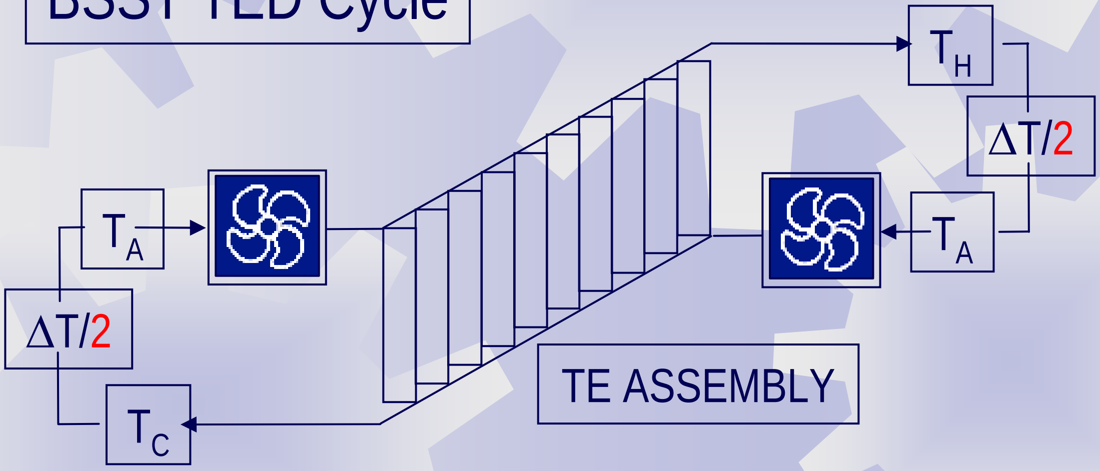
December 13, 2005

Modified from: http://www.its.caltech.edu/~jsnyder/thermoelectrics/

Standard TED Cycle



BSST TED Cycle



All TE components experience the same temperature differential, $\Delta T = T_H - T_C$

$$COP_{MAX} = \frac{T_c}{\Delta T}\left(\frac{M - 1 - \frac{\Delta T}{T_c}}{M + 1}\right)$$

$$M = \sqrt{ZT_A + 1}$$

Same system $\Delta T = T_H - T_C$, but each TE component experiences temperature differential of $\Delta T/2$

$$COP_{BMAX} = \frac{2T_C}{\Delta T}\left(\frac{M - 1 - \frac{\Delta T}{2T_C}}{M + 1}\right)$$

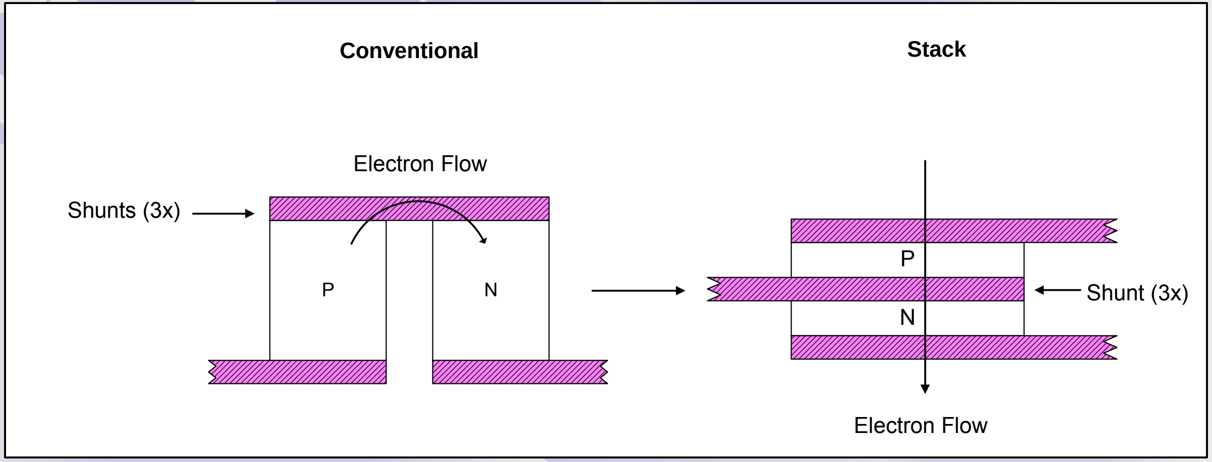
Stack Design

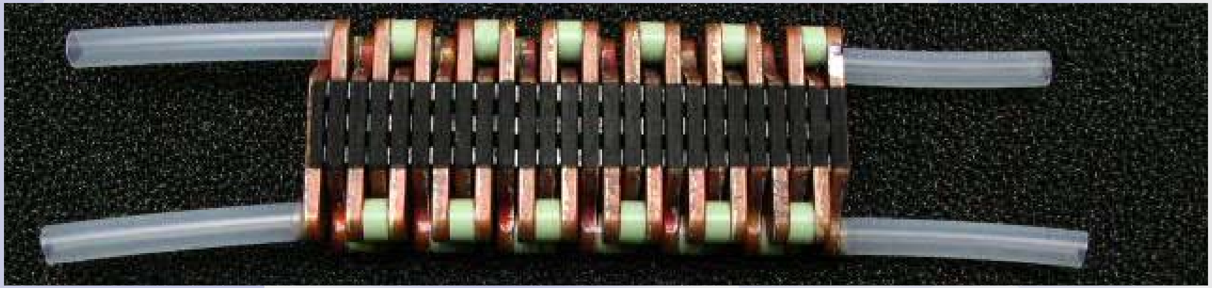
Direct, short current paths

TE element size is scalable to match power output requirement

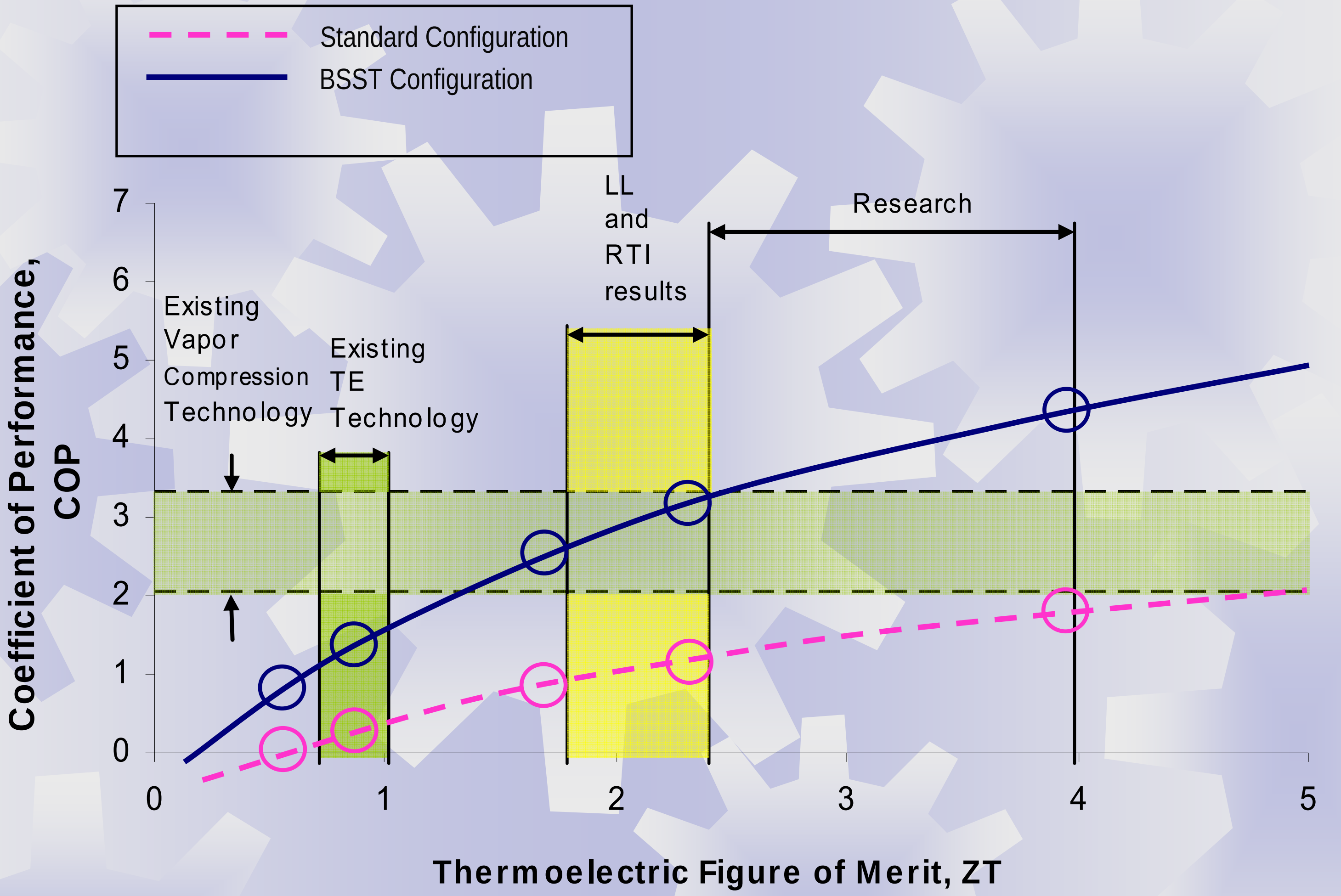
Requires less TE elements

Heat flux paths can have fewer thermal interfaces





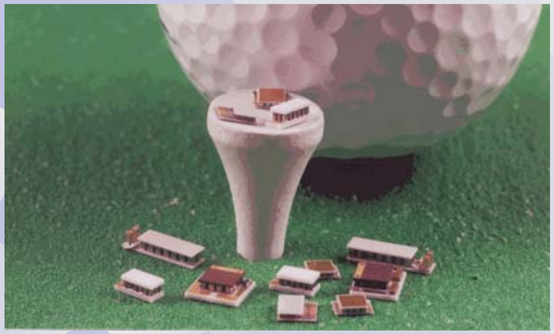
Thermoelectric Cooling Efficiency



COP as a function of ZT (today and projected) when advanced materials and/or Advanced thermodynamic cycles are implemented.

Cooling/Heating Applications

IR Sensor Coolers,
Melcor

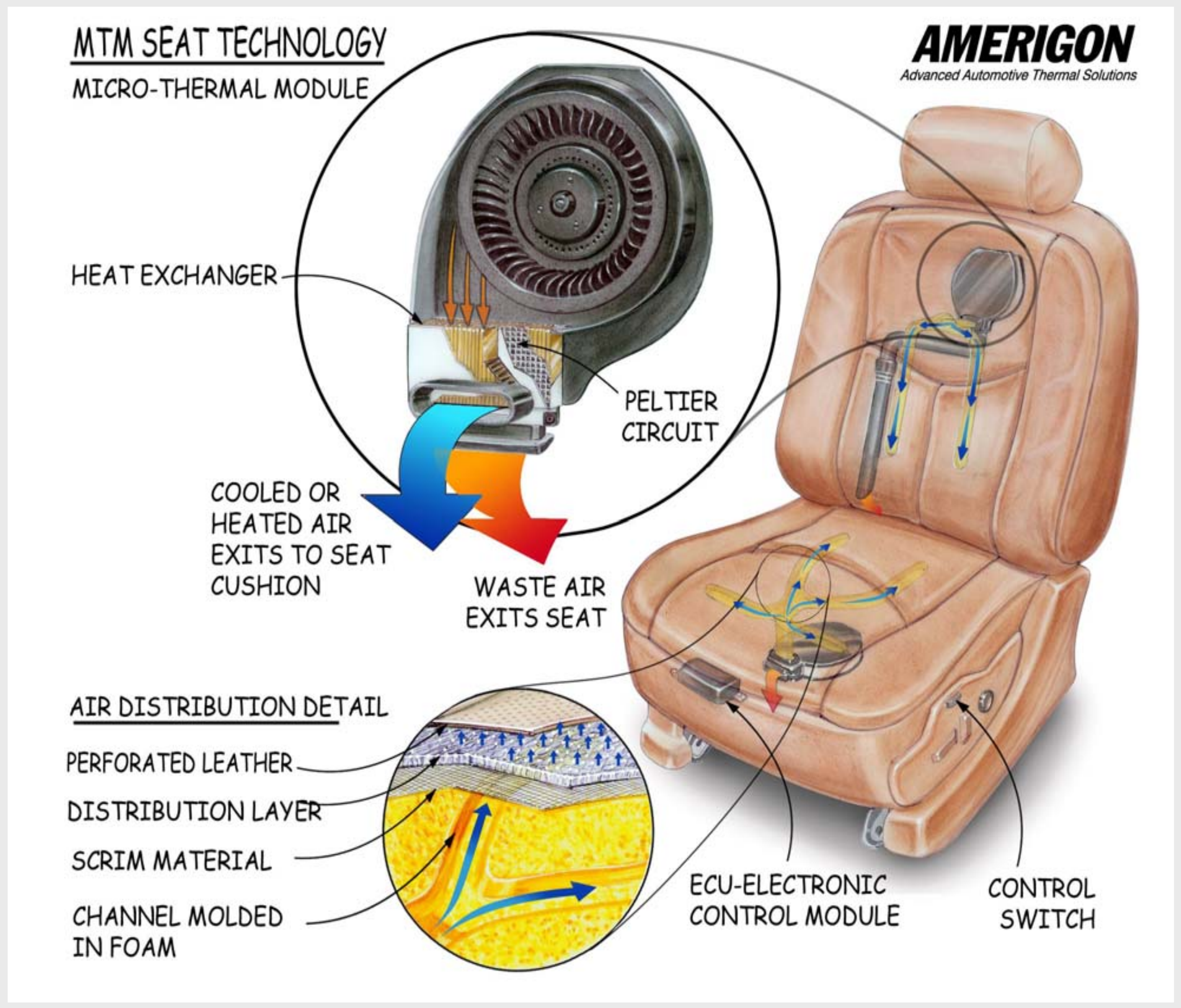


Laser and Telecom Coolers,
Marlow Industries

Beverage Heater Cooler
Tellurex

Desktop Heater/Cooler,
Herman Miller

Heated / Cooled (CCS^{TM}) Seat Design



Amerigon Current CCS™ Vehicle Lines


2007 Escalade (ESV, EXT)


Nissan Cima


Cadillac (XLR,DTS)


Toyota Century


Toyota Celsior*


Lincoln Navigator


Ford Expedition


Nissan Fuga


2006 Buick Lucerne


Lincoln LS


2007 Range Rover


Lexus LS 430*


Hyundai Equus*


2006 Lincoln Zephyr


Infiniti (Q45, M45)


Mercury Monterey

* Four Seat Systems

Zonal Hybrid HVAC

Effective A/C Performance

- Average system level efficiency similar to electric motor drive 2-Phase system
- Rapid response time
- Average system level heating efficiency 2.5 times that of PTC heater

Superior Heating Performance

- Rapid response time under most operating conditions
- Operates with engine off

Hybrid Integration

- Electrically powered with no added weight, size, or complexity
- Operates efficiently with engine off
- Long term HVAC solution

Heating Mode		**Cooling Mode**	
Q_h (W)	630	Q_c (W)	800
Q_{in} (W)	240	Q_{in} (W)	220
COP	2.63	COP	3.64
Airflow, L/s	24.2	Airflow, L/s	65
Water flow rate, cc/s	60	Water flow rate, cc/s	60
ΔT air, ^{0}C	20	ΔT air, ^{0}C	-10
ΔT water, ^{0}C	-1.4	ΔT water, ^{0}C	2.2
T air inlet, ^{0}C	25	T air inlet, ^{0}C	25
T water inlet, ^{0}C	25	T water inlet, ^{0}C	25
ΔP air, KPa	0.075	ΔP air, KPa	0.075
DP water, KPa	2.1	DP water, KPa	2.1

Power Generation Applications

Global TEG on Natural Gas Line,
Global Thermoelectric

Thermopile Generators,
Honeywell

freedomCAR & vehicle technologies program

Waste Heat Recovery for Fuel Efficiency Improvement

BSST
innovative solutions
in temperature control

NETL

BMW

Visteon

PURDUE
UNIVERSITY

NREL

NASA
Jet Propulsion Laboratory
California Institute of Technology

freedomCAR & vehicle technologies program

In 2004 the US DOE Freedom Car Program office started 4 Thermoelectric Waste Heat Recovery Programs

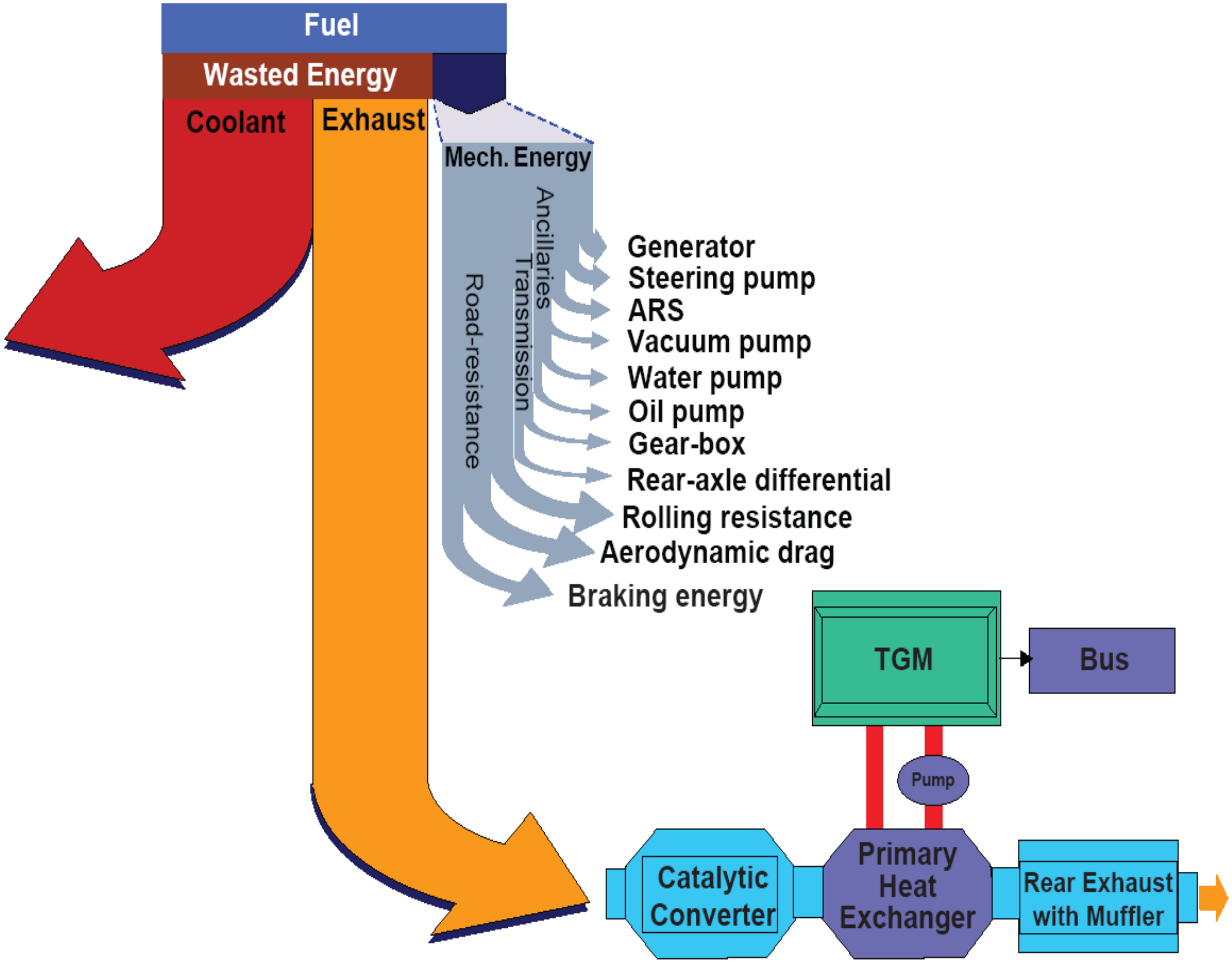
BSST and General Motors began programs to install systems in passenger vehicles

Michigan State University and United Technologies Corporation began programs to install systems in heavy diesel engine vehicles

The DOE Program objectives include:

- 10% fuel efficiency improvement
- Reduced emissions
- A demonstrated path to commercialization and economic feasibility assessment

System Block Diagram



BSST Waste Heat Recovery Program Overview

BSST was awarded a Prime Contract to model, design, build and test a Thermoelectric Waste Heat Recovery System for passenger cars

The $6.2M program was organized into 4 development phases

- **Phase 1** (Q3 04 thru Q2 05) A system architecture was created and captured in a bumper to bumper vehicle simulation model (ADVISOR). Subsystem design requirements were set and initial system FE savings were shown to reach 12%
- **Phase 2** (Q3 05 thru Q4 06) Key subsystems (Primary Exhaust Gas Heat Exchanger, Thermoelectric Generator Module TGM), Power Conversion Electronics) were built and tested.
- **Phase 3** (Q1 07 thru Q1 08) Two full scale TGMs are planned:
    - A BiTe TGM, has been built and tested demonstrating > 500 watts electrical power output.
    - A high temperature TGM will be built and tested by early Q1 07 (>500 watts)
    - The Waste Heat Recovery System will be operated on a test bench using a hot gas torch to provide a source of heat.
- **Phase 4** (Q2 07 thru Q4 07) The Waste Heat Recovery System is integrated and tested with BMW’s in line 6 cylinder engine on an engine dynamometer at the Federal Laboratory in NREL Colorado

Thermal Management.
Thermoelectric Generator.

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

FreedomCAR & Fuel Partnership

Visteon®

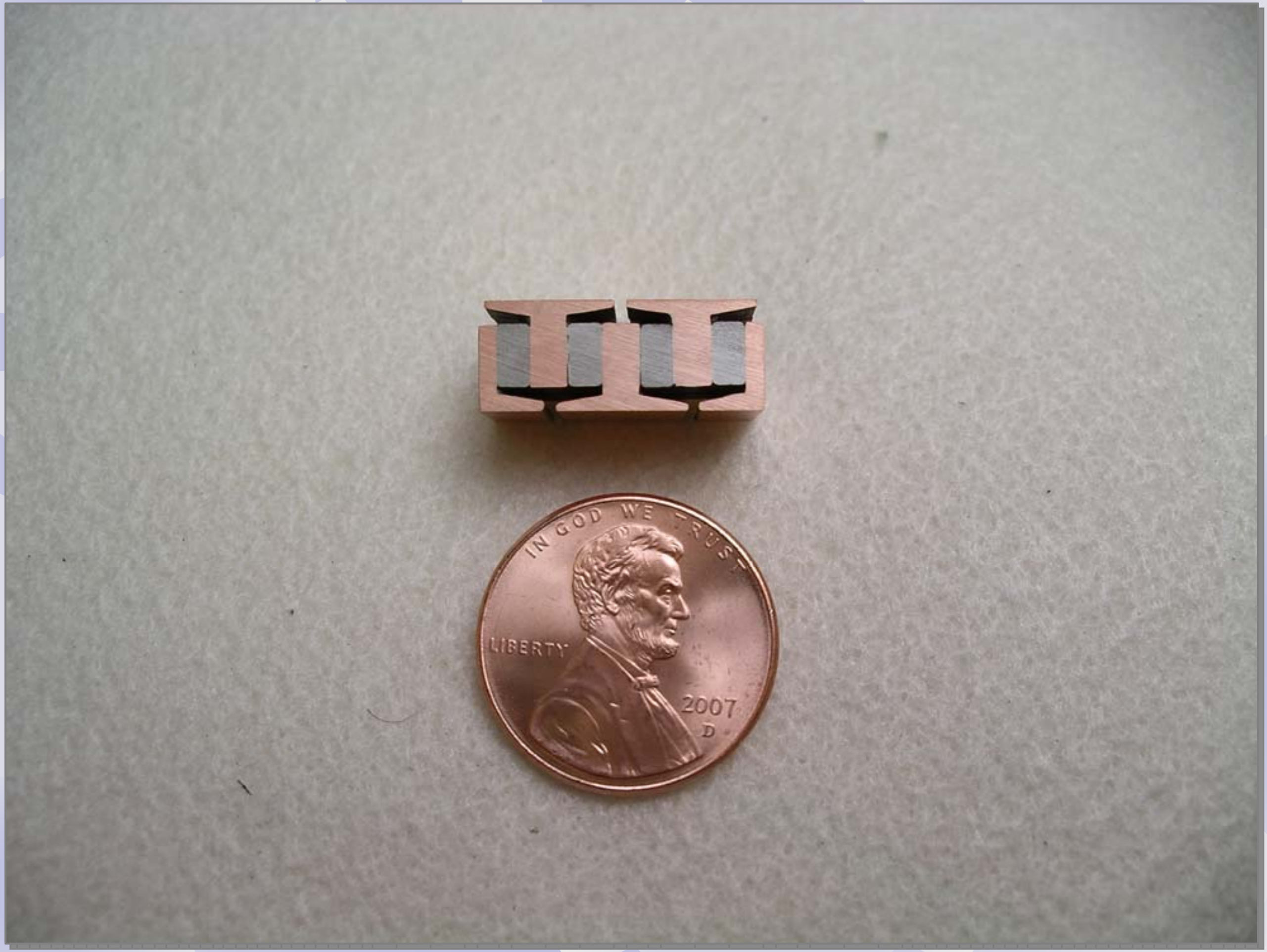
BSST
innovative solutions
in temperature control

BMW

MINI

TGM Subassemblies

2^{nd} Generation Bi_2Te_3 Subassembly



Representative National Projects

USA

- ONR/DARPA (1992 to Present)
- Multiple University Research Initiatives
- Direct Energy Conversion Program
- Department Of Energy
- Waste Heat Recovery For Efficiency Improvement
- NASA
- Thermoelectric Power Generators for unmanned spacecraft

Japan

- New Energy and Industrial Technology Organization (NEDO) Japanese National Project, from 2002 – 2007, 5 year project, titled "The Development for Advanced Thermoelectric Conversion Systems"
- Efficiencies = 15% with $\Delta T = 550C$
- Project includes industrial partners Komatsu, Toshiba, and Yamaha, as well as IHI, Ube Industries, and Eco21
- Prof. Kajikawa from Shonan Institute is Project Leader

European Union

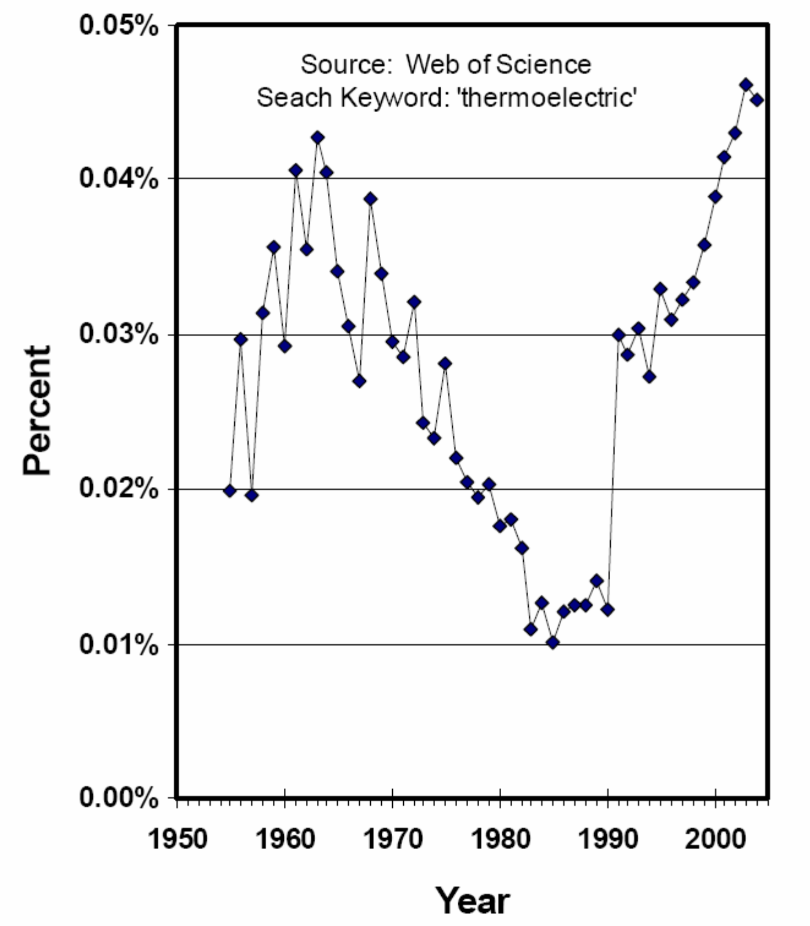
- European Thermoelectric Society & European Conference on Thermoelectrics
- NanoThermal Project (2000 – 2003)
  - "Nano-engineering of high performance thermoelectrics", European Union-funded and coordinated by M. Muhammed of the Royal Institute of Technology, Sweden
  - Synthesis of nano-particle materials with reduced thermal conductivity.
- NAMTEC
  - "European Thermoelectric Network of Excellence", organized by D. Rowe of University of Wales, Cardiff and P. Rogl of University of Wien with 116 research groups throughout Europe, 26 countries. TE material research, scale up, and applications

Selected US Waste Heat Recovery Opportunities

Heat Source	Target CO_2 Reduction	Fossil Fuel Reduction	Enabling Average ZT	Target Cost/Watt	Development Activity
Car, Van, Truck, Bus Exhaust	5-10%	Significant	~1.2	$1.00	Worldwide
Car, Van, Truck, Bus Engine Coolant	1.5-3%	Significant	~2.0	$1.00	Pending improved materials
Glass Production	0.3-1.1%	Moderate	~2.0	<$5.00	Study Phase
Primary Aluminum Production	NA	Low	~2.0	<$5.00	Study Phase
Molten Metal Furnaces	NA	Low	~2.0	<$5.00	Study Phase
Industrial/Commercial Cogenerators	4-7%	Significant	~1.0	<$5.00	Study Phase

Things to Come

Publications in the Web of Science database with the keyword 'thermoelectric' as a percentage of all publications in the database from 1955-2003



Graph Adapted from: Vining, Cronin B., "ZT ~ 3.5: Fifteen Years of Progress and Things to Come," *ZT Services*

Summary

Important advances in TE technology have occurred over the last 5 years. It is anticipated that in the next several years TE materials with a ZT of 1.2 will become commercially available. These lead to opportunities for waste heat recovery that can have an impact of societal importance to reduce CO_2 emissions and oil consumption.

Near term waste heat recovery technology is best suited to home, light industry and transportation applications.

TE waste heat recovery technology also provides enhanced performance of larger systems coupled with fuel cell, diesel power generation and solar photovoltaic systems.

Energy saving opportunities include heat pumps, zonal environmental conditioning and remote, small scale power generation

Process and other industry applications are enabled at ZT of 2.0.