U.S. Department of Energy
Energy Efficiency and Renewable Energy
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Vehicle Technologies Program

Vehicular Applications of Thermoelectrics

John Fairbanks
Office of Vehicle Technologies
Energy Efficiency and Renewable Energy
Department of Energy
Washington, DC

Diesel Engine-Efficiency and Emissions Research (DEER) Conference
Dearborn, Michigan
August 4-7,2008

U.S. Department of Energy
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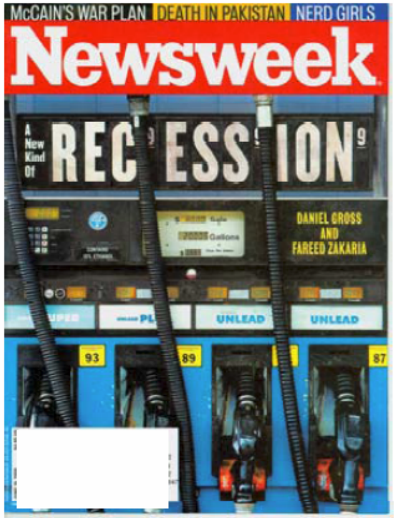
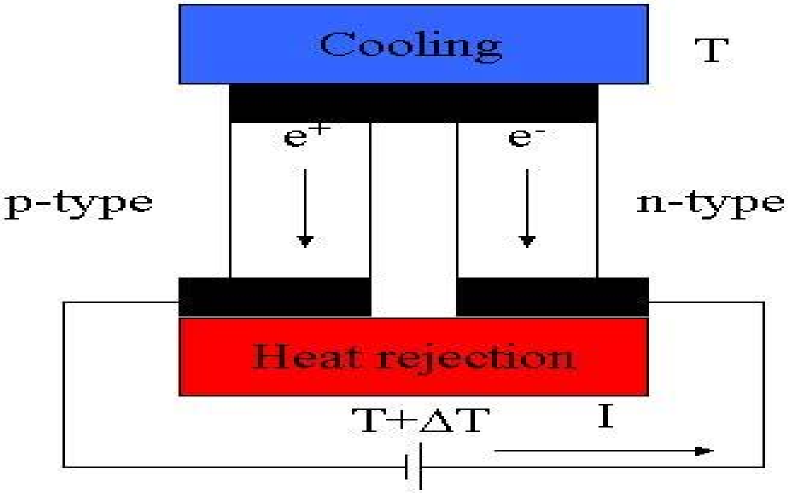
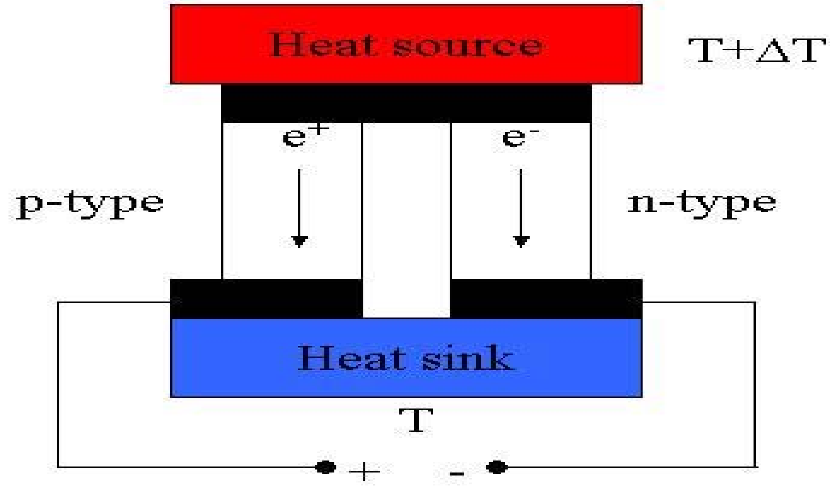
Energy Impacting Issues Ahead



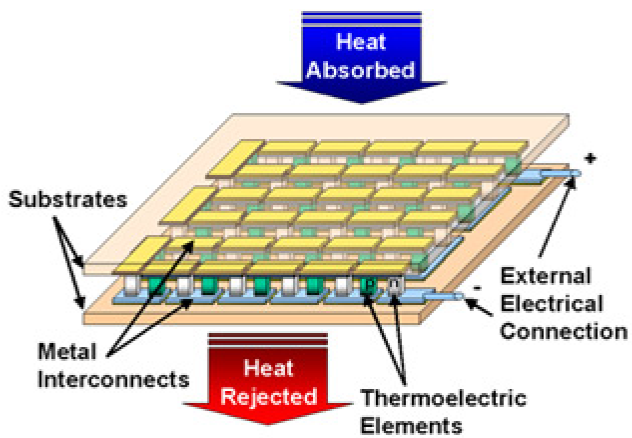
Thermoelectric Modules



Refrigeration



Power generation



OVERVIEW

- European Thermoelectric Programs
- Japanese Thermoelectric Programs
- Potential Improvements in Thermoelectrics
- DOE/NETL Vehicular Thermoelectric HVAC (New Start)
- DOE/NETL Vehicular Thermoelectric Generator Projects

- ***European Thermoelectric Programs***

TE applications: heat recovery from exhausted gases

CENTRO RICERCHE FIAT

Reduced Energy Consumption by Massive Thermoelectric Waste Heat Recovery in Light Duty Trucks

HeatReCar - EU project

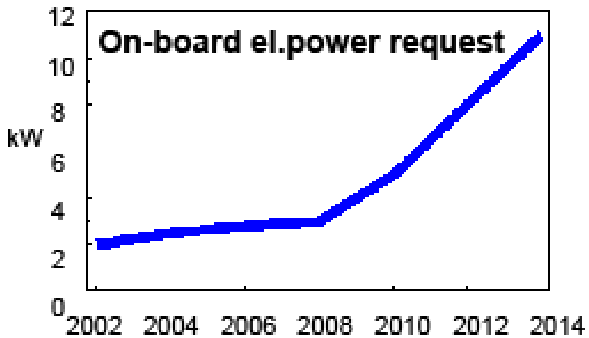
SEVENTH FRAMEWORK PROGRAMME

SIEMENS	Siemens - Germany
ROM INNOVATION	ROM Innovation -France
CRF CENTRO RICERCHE FIAT	CRF - Italy
BOSCH	Bosch - Germany
Termo-Gen AB	Termo-gen AB - Sweden
Fraunhofer IPM	Fraunhofer IPM - Germany
Valeo	Valeo - France

The CAR evolution

CENTRO RICERCHE FIAT

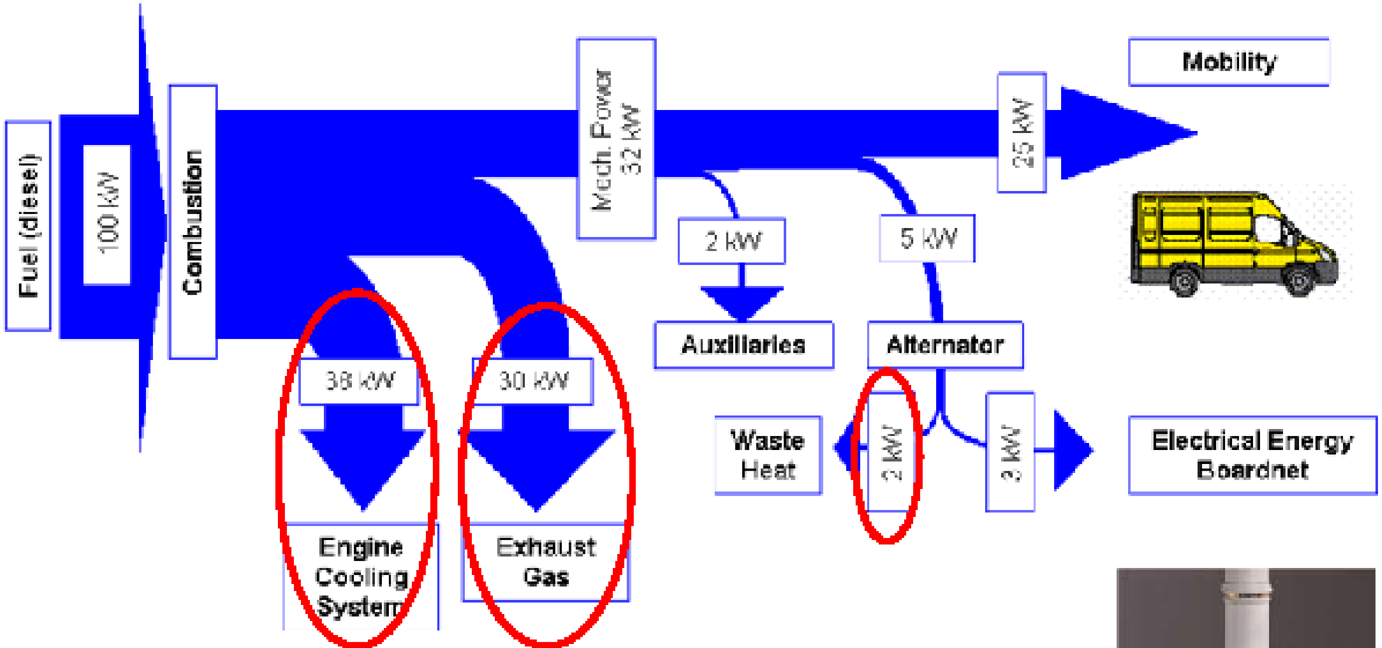
- The introduction of electronics and μ-systems has increased 15-20% in the last 5 years
- More than 60 actuators and 80 sensors today installed in the car
- The electronics today represent the 20% of the cost, expected 40% in 2015



The CAR is eager for electrical energy!!!

CENTRO RICERCHE FIAT

Vehicle heat release



About **70%** of fuel chemical energy is lost as **HEAT**

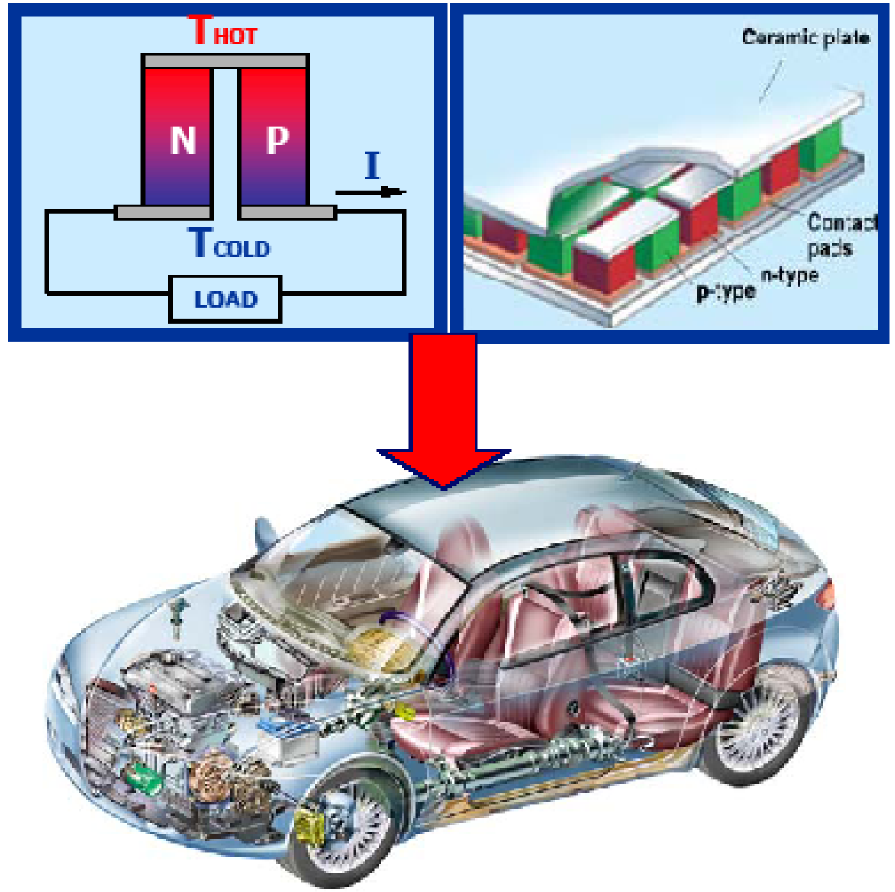
The CAR is an unintentional heat source!!!

Thermoelectrics On-board

CENTRO RICERCHE FIAT

Need for ELECTRICAL ENERGY

Abundance of WASTE HEAT



TE applications: distributed energy generation

CENTRO RICERCHE FIAT

Thermoelectricity for Mobile Systems

THERMOBILE - *under evaluation*

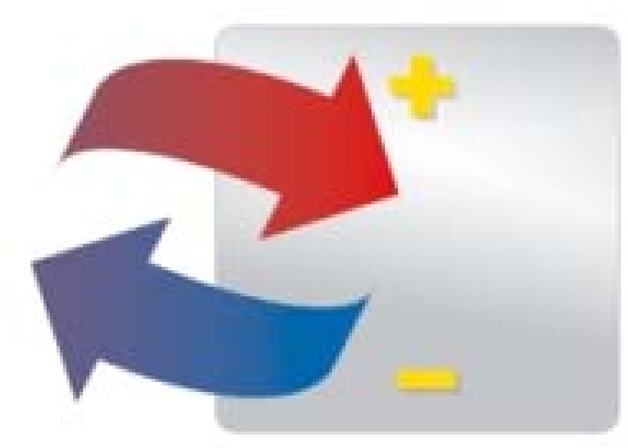
SEVENTH FRAMEWORK PROGRAMME

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	CNRS – France
CRF CENTRO RICERCHE FIAT	CRF – Italy
SNCF	SNCF – France
cea	CEA – France
EMPA	EMPA – Switzerland
DTU	DTU – Denmark
BOSCH	BOSCH – Germany
Termo-Gen AB	Termo-Gen – Sweden
BASF The Chemical Company	BASF - Germany

1st Thermoelectrics Conference

An Opportunity for the Automotive Industry?

Date: 23.10.2008 - 24.10.2008
Location: Berlin



The demand for mobility and transportation is growing worldwide. Consequently, the demand for energy is rising too. In the light of limited fossil energy resources and production capacities as well as increasing impacts on the environment and advancing climate change, the automotive industry is also facing expectations to further reduce pollutant emissions, fuel consumption and CO2 emissions of future motor vehicles. Against the backdrop of rising petroleum and thus fuel costs, new government regulations and consumer expectations, vehicle developers are looking for new, innovative technologies and concepts for sustainably improving the environmental compatibility, energy efficiency, safety, comfort, quality and economy of coming car generations. In particular, all existing potentials are being exploited to reduce the consumption of primary fossil energy by traffic. In addition to the development strategies pursued to date, approaches to substitute primary energy with ambient and lost energy are now gaining significance.

Over the next 5 years, the development of efficient thermogenerators and systems suitable for in-vehicle application will demand tremendous efforts from all parties concerned while at the same time, incurring high costs. The conference sets out to provide developers and users with the opportunity to exchange experience.

Conference Chair
Daniel Jänsch, IAV GmbH

Conference Committee
Dr. Johannes Liebl, BMW Group
Dr. Karsten Michels, Volkswagen AG
Prof. Karl-Ernst Noreikat, Daimler AG
Dr. Thomas Heckenberger, Behr GmbH & Co. KG
Dr. Rolf Jebasinski, J. Eberspächer GmbH & Co. KG
Rolf Brück, Emitec GmbH
Roger Deckers, Continental AG
Dr. Harald Böttner, Fraunhofer-Gesellschaft
Dr. Eckhard Müller, DLR e.V.
Dr. Rüdiger Schütte, Evonik Degussa GmbH
Dr. Georg Degen, BASF SE
Dr. Anke Weidenkaff, EMPA
Prof. Frank Behrendt, TU Berlin
Prof. Peter Steinberg, TU Cottbus
Prof. Hans Zellbeck, TU Dresden
Daniel Jänsch, IAV GmbH
Mike Laudien, IAV GmbH

- **European Activities (FP7)2008-2010**
- **Advanced Material Architectures for Energy Conversion**
- **NANOTERM**
- **Behr GmbH and Co KG –Germany (Brehn Holger)**
- **Mensh- Marketing –Technik- Germany(Anett Dylla)**
- **Consiglio Nazionale Delle Recerche-Italy(Dr Carlo Gatti)**
- **Thermugen - Sweden (Lennart Holmgren)**
- **Univesity of Aarhus – Denmark (Professor Bo Iversen)**
- **University of Cardiff- Wales (Dr Gao Min)**
- **Dantherm- Denmark (Paw Mortensen)**
- **German Aerspace Centre – Germany (Dr Eckhard Mieller)**
- **Chalmers Tekniska Hagskolan –Sweden (Dr Anders Palmquist)**
- **PANCO –Germany (Dieter Platzek)**
- **Aalbory University - Denmark (Dr Lasse Rosendahl)**
- **German Aerspace Centre – Germany(Christian Stewe)**

- ***Japanese Thermoelectric Programs***

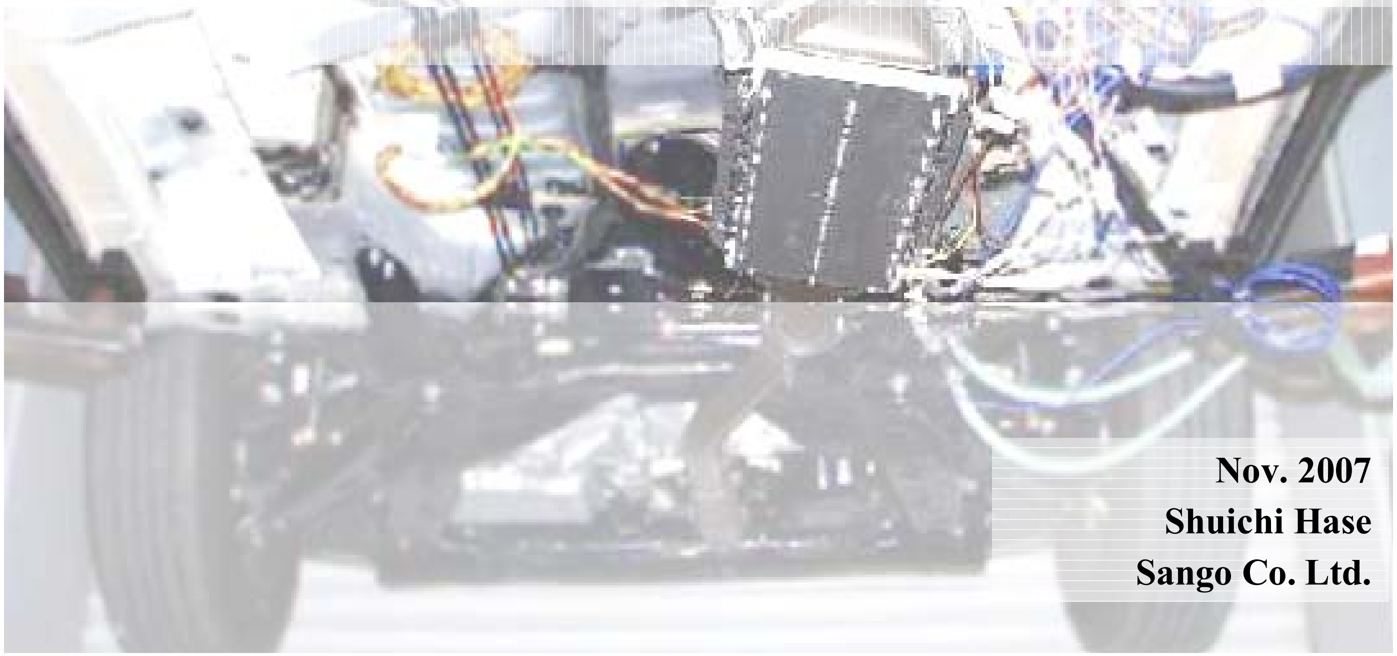
Thermoelectric Element at Toshiba Material

April 2007

This thermoelectric element was developed in April 2007 by Toshiba Material. The module has a maximum of 3.1 W/cm2 output at a temperature difference of 735°C (high temperature: 800°C, low temperature: 65°C). The substrate is composed of Si_3N4. The targeted application is the generation of electricity from automobile exhaust gas.

SANGO

Heat-Recovery for ICE Automobiles
and
Thermal Electric Generation



Nov. 2007
Shuichi Hase
Sango Co. Ltd.

[illegible]

[illegible]

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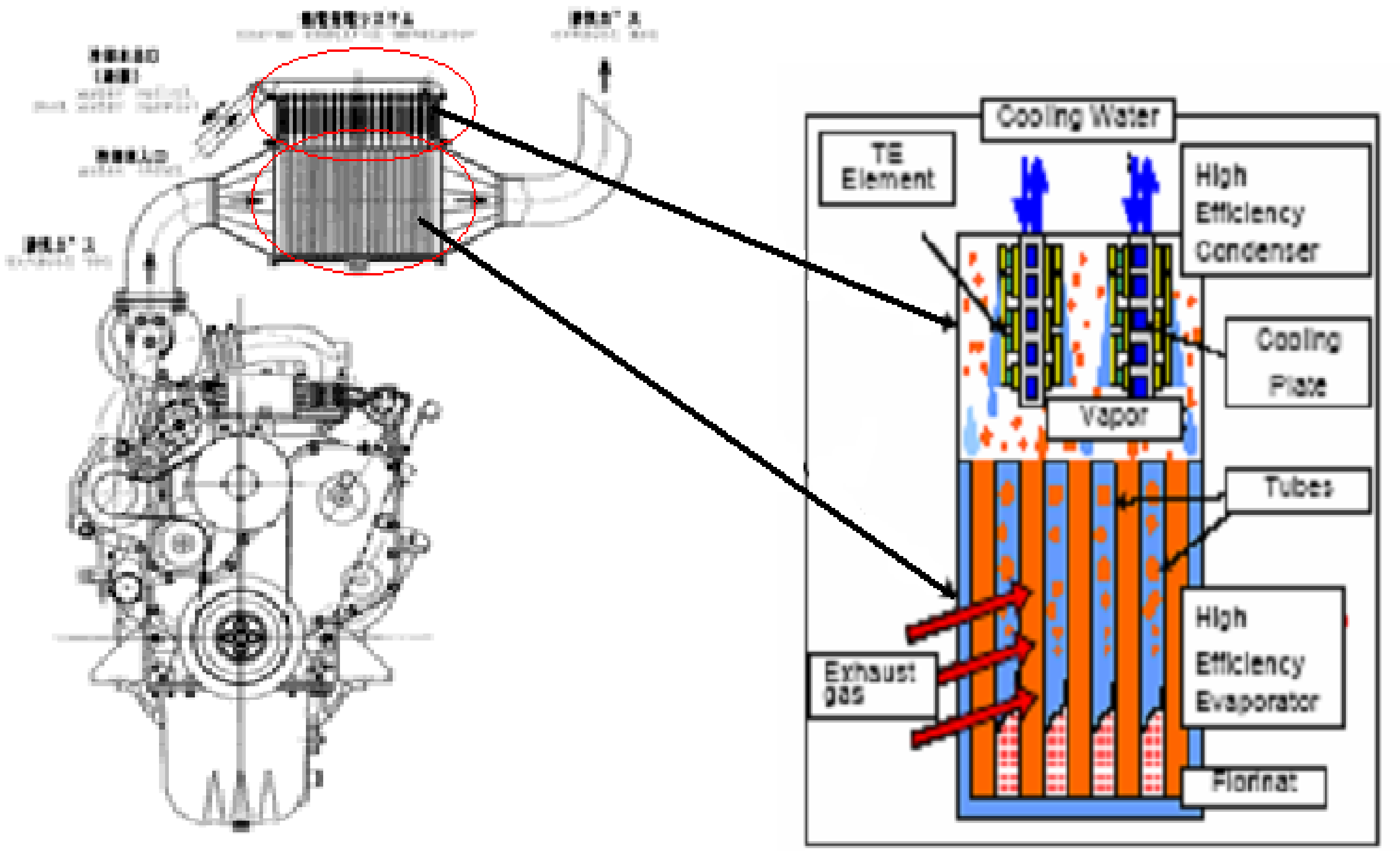
[illegible]

JATeCS Project

Japanese National Project on Development for Advanced Thermoelectric Conversion Systems

Project Leader : Dr. Takenobu KAJIKAWA
Engineering Advancement Association of Japan (ENAA)
eco21, Inc.
Ishikawajima-Harima Heavy Industries Co., Ltd.
Komatsu Ltd.
TOSHIBA Corp.
UBE Industries, Ltd.
YAMAHA Corp.

Komatsu Diesel Engine with Thermoelectric Generator



Courtesy of Dr. Takanobu Kajikawa, Project Leader, Japanese National Project on Development for Advanced Thermoelectric Energy Conversion Systems

Object and Goal

- Object
  - To Contribute to the Countermeasure of Global Warming by Thermoelectric Power Generation Technology Recovering the Waste heat from Industrial and Private Sectors
- Goal
  - TE Conversion Modules
    - Interim : Conversion Efficiency 12% at $\Delta T=550K$
    - Final : Conversion Efficiency 15% at $\Delta T=550K$
  - Establishment of TE Power Generation Systems

Target Cost for Practical Use

- Advanced Thermoelectric Conversion Module
  - Cost : Less than Yen100/W
    - on the Basis of 2 Million Modules / Annual Production

- Thermoelectric Power Generation System
  - Payback Period : Less than 7 Years

Contents of R&D - 1

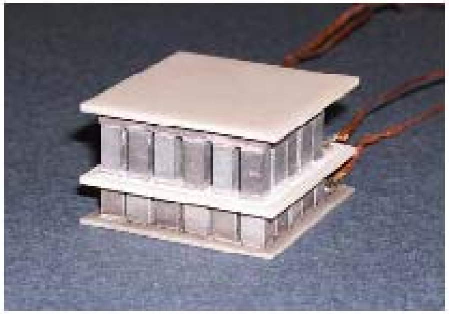
- Development on Advanced Thermoelectric Elements and Modules for both High and Low Temperature Application, such as :

- Silicide
- Skutterdite
- Zn-Sb

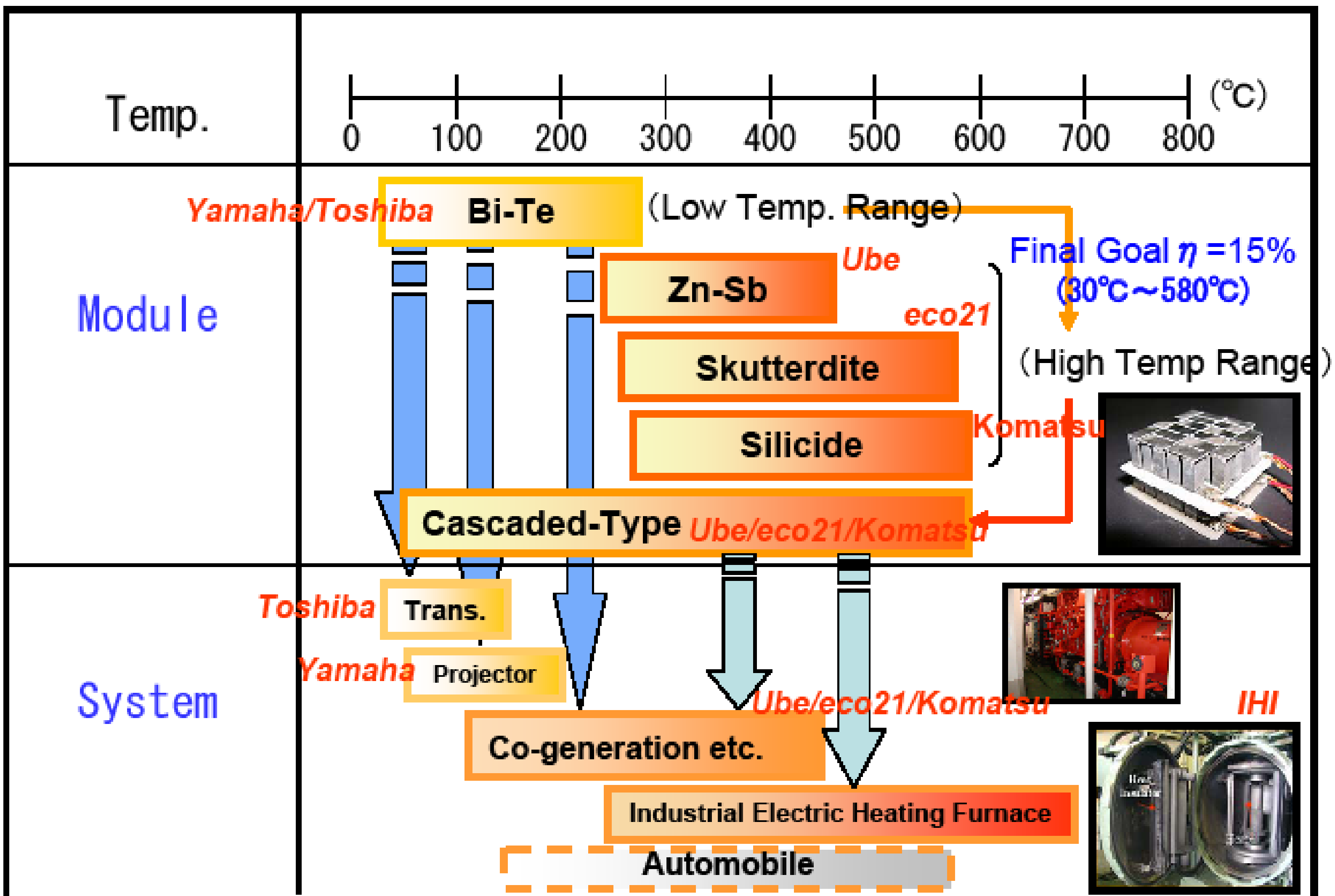
&

- Bi-Te

Cascaded

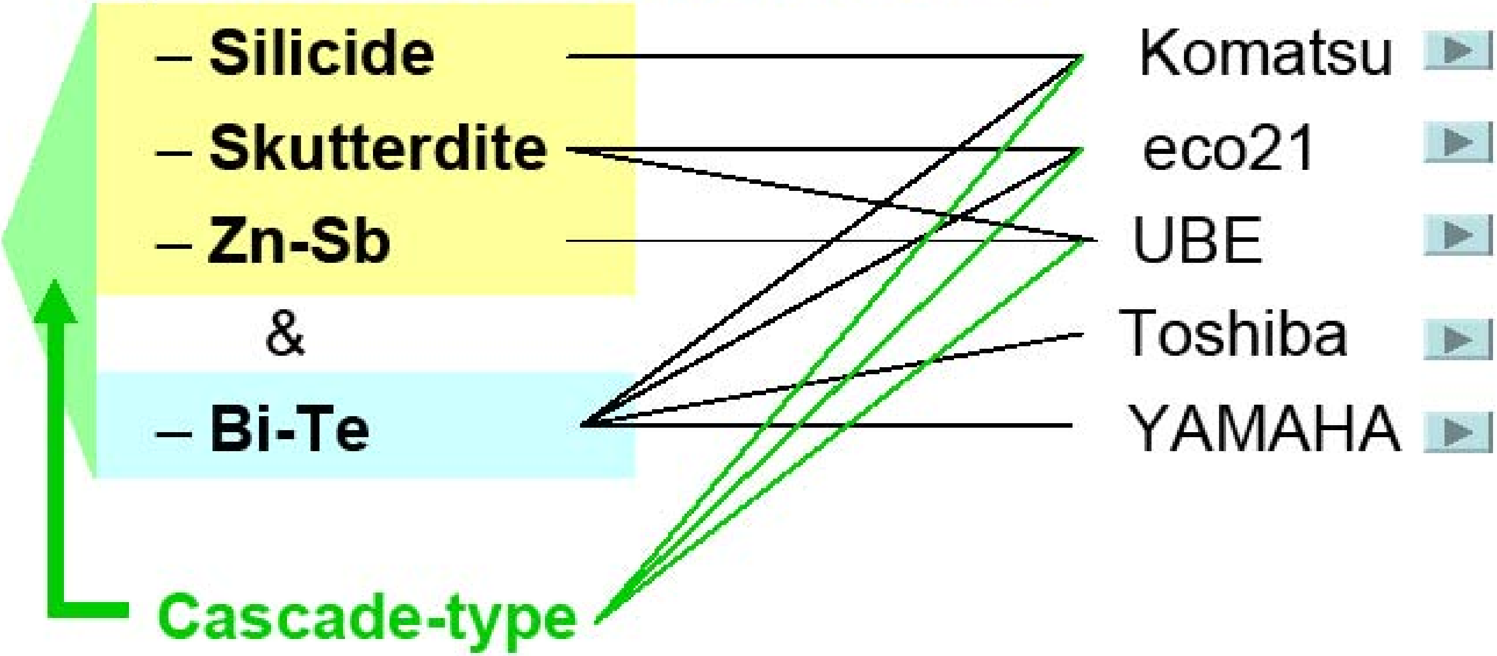


Thermoelectric Module & Application Temp. Range



Interim R & D Results

(1) Thermoelectric Modules



Interim Results of Modules

Temp. range			Th	Tc	ΔT	Efficiency (%)		
High	Low		℃	℃	K	Interim Goal	Achieved	Final Goal
Zn-Sb		*Ube*	450	250	200	4.5	4.5	5.5
Zn-Sb	Bi-Te	*Ube*	450	50	400	–	-	11.0
Co-Sb	Bi-Te	*eco21*	427	27	400	9.0	9.9	11.5
Silicide	Bi-Te	*komatsu*	580	30	550	12.0	12.4	15.0
	Bi-Te	*Toshiba*	130	30	100	3.6	3.0 *	4.2
	Bi-Te	*Yamaha*	200	50	150	3.5	5.5	5.3

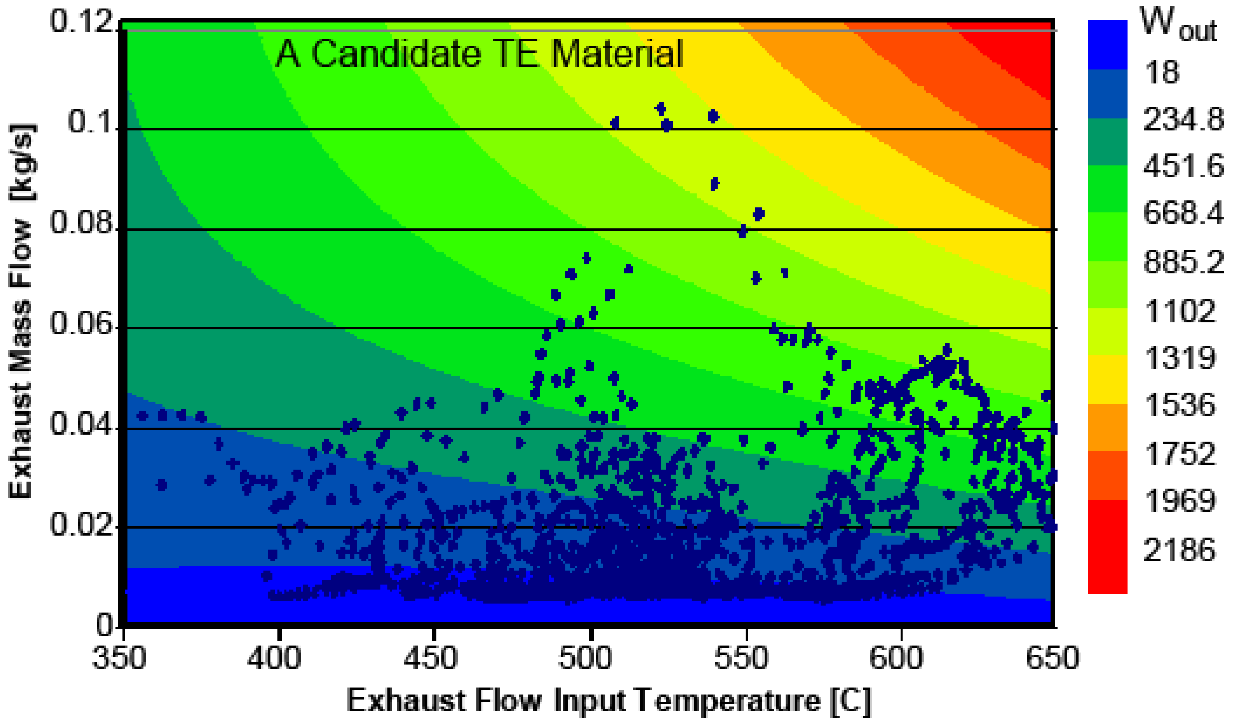
* Expected to Achieve the Interim Goal

Based on NASA-JPL Studies

- ***Potential Improvements in Thermoelectrics***

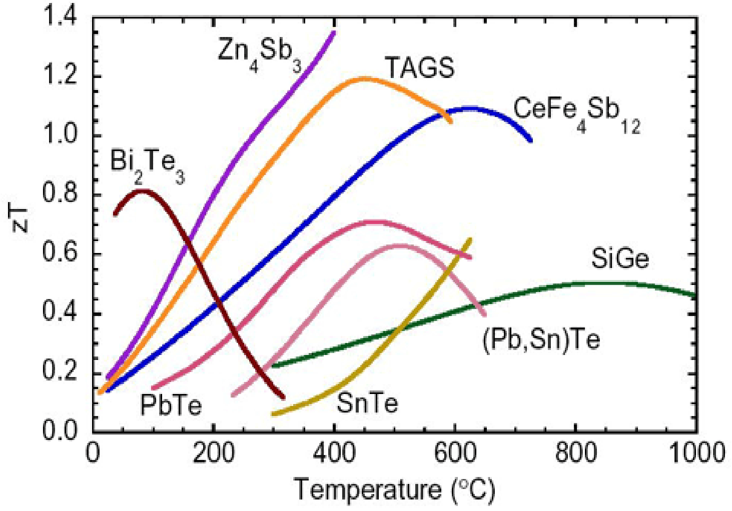
GM

Overlay of TE System Efficiency and Expected Exhaust Conditions

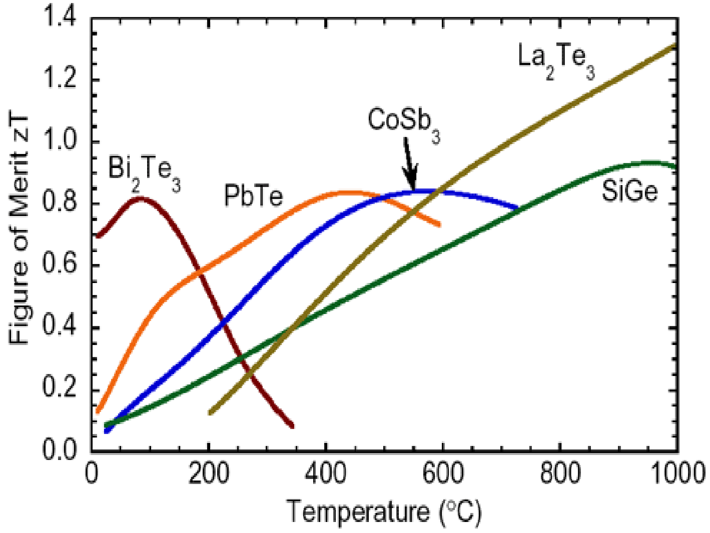


R&D CENTER

Current TE Materials



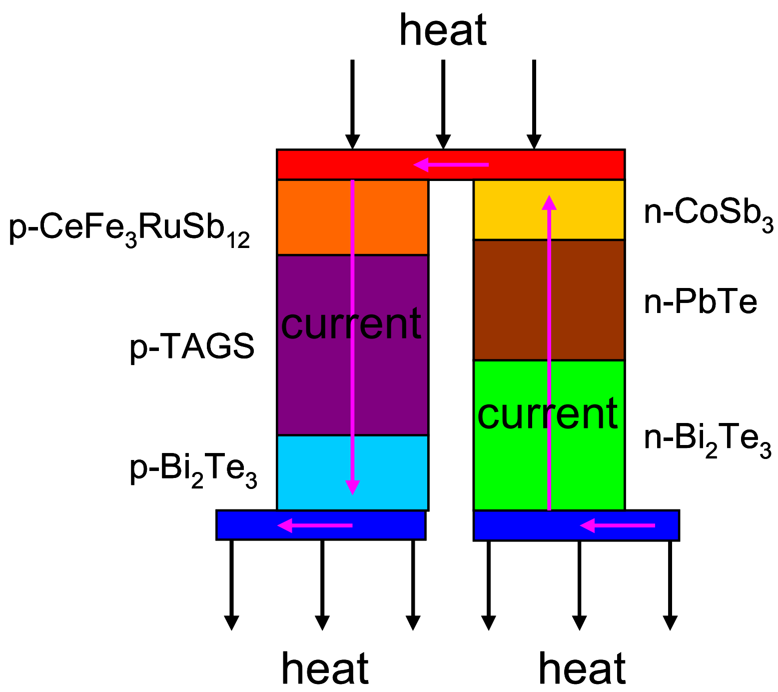
P-type TE material

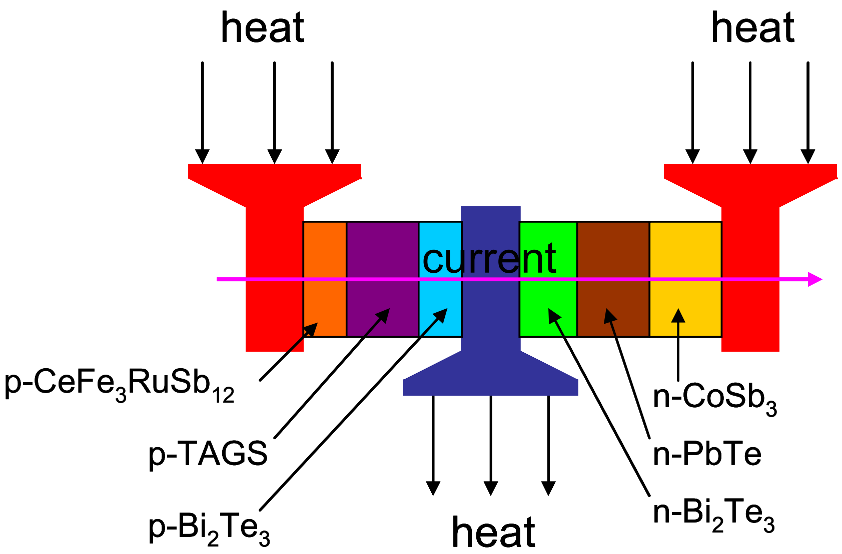


N-type TE material

Ref: http://www.its.caltech.edu/~jsnyder/thermoelectrics/

BSST Y-Segmented TE Configuration

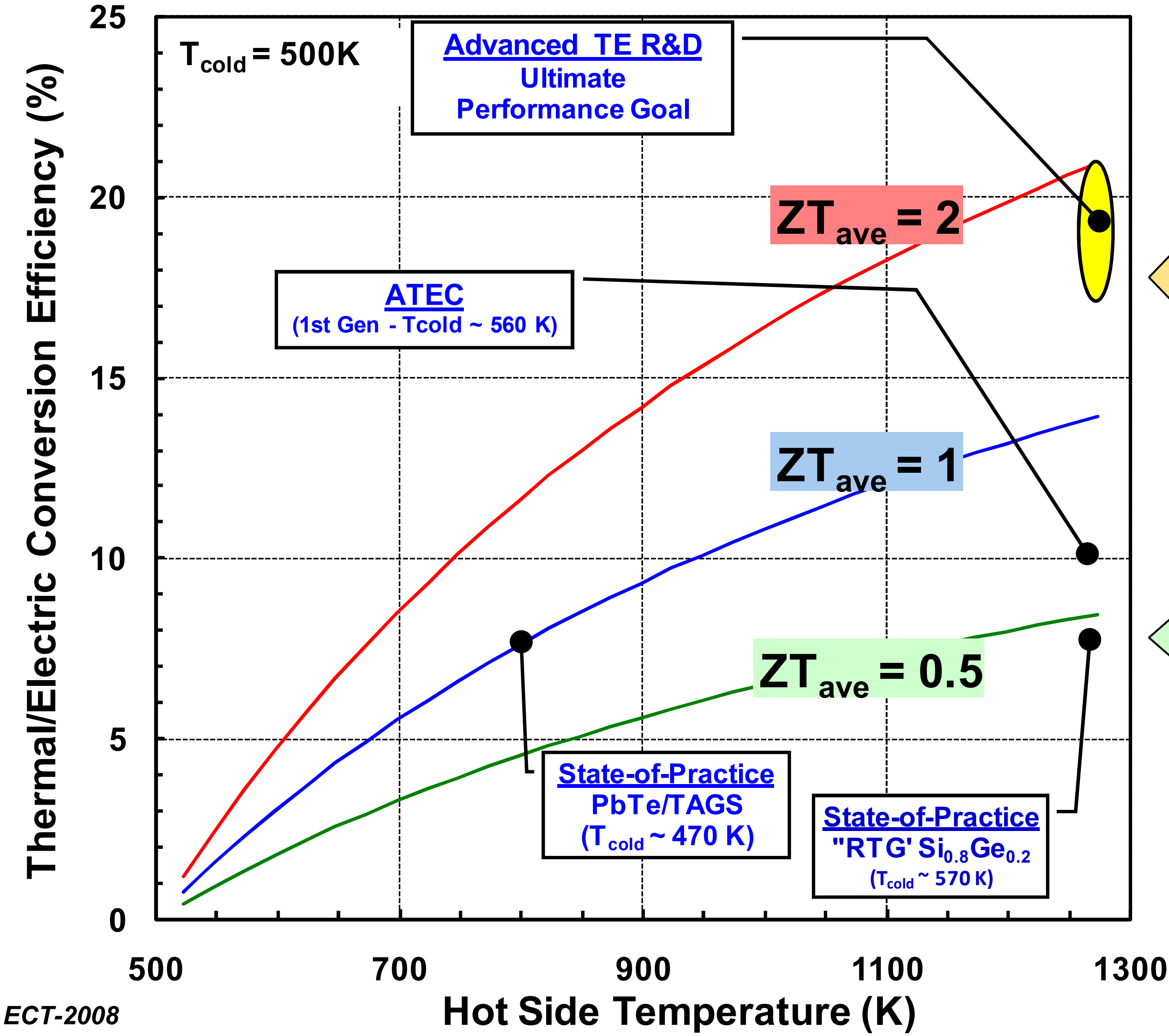




- Traditional configuration
- BSST "Y" configuration

Advanced TE Research &Technology Program
TE Materials Performance Objective

TE conversion efficiency as a function of hot junction temperature and ZT



$$\eta_{max} = \underbrace{\frac{T_{hot} - T_{cold}}{T_{hot}}}_{Carnot} \; \underbrace{\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}}_{TE\ Materials}$$

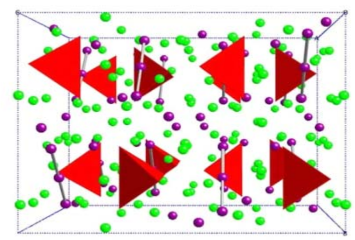
Materials

Goal for Advanced TE Materials Integrated in Segmented Configuration for for maximizing ZT over Wide Wide ΔT

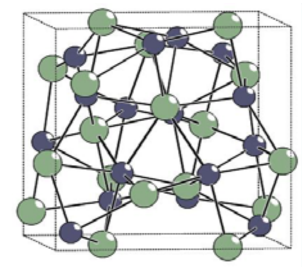
TE Materials for RTGs Flown on NASA Missions Missions

Why do we think that ZT_{ave} > 1.5 can be done?

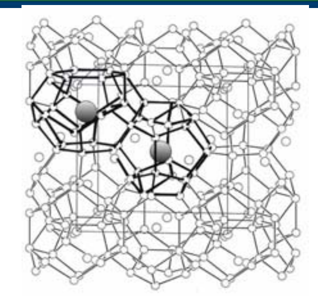
- **Theoretical calculations have predicted ZT_{max} ~ 4-8**
  - **For "engineered" material structures**
- **Recent good results on new bulk materials**
  - **Peak ZT values ~ 1.5**
  - **For Zintl, $La_{3-x}Te_4$ and PbTe-based complex structure materials**
- **High ZT reported on nanostructured thin films**
  - **Peak ZT values ≥ 2.5**
  - **For Bi_2Te_3/Sb_2Te_3 superlattices**
  - **For PbTe-based quantum dot thick films**



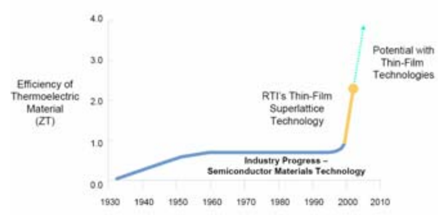
Zintl Phases
PbTe-Based Mat'ls



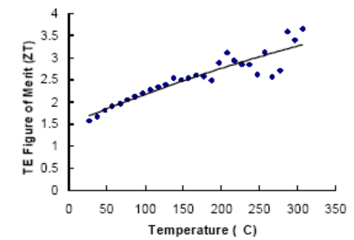
$LaTe_y$-based
compounds

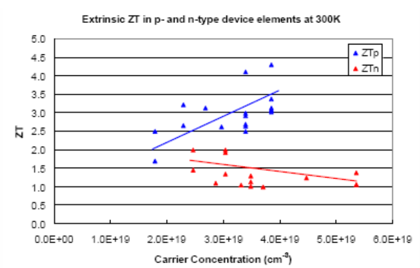


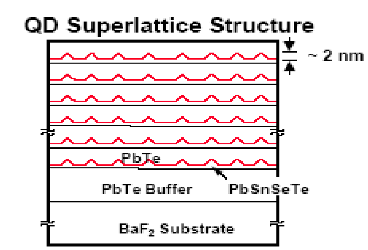
Si, Ge-based
Clathrates



Ref : Nature, 413, 597 (2001)



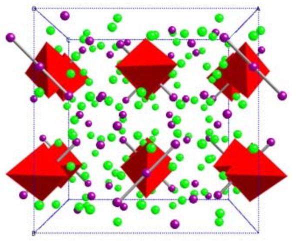




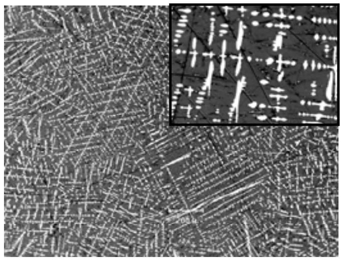
Combine "Complex Bulk" and "Low Dimensional" Approaches!

- Achieve High ZT in Practical Bulk Materials
- Segment for Operation Across large ΔT

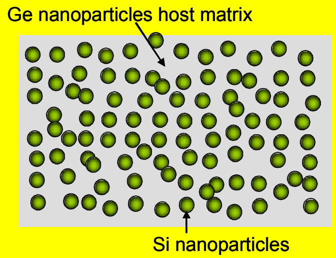
Nanostructured Bulk TE Materials Through Consolidation of Nanoparticles



Rare Earth Compounds and Advanced Refractory Complex Structure Materials



"Self-Assembling" Thermally Stable Nanostructured Bulk Materials



"Force Engineered" Nano Bulk Si-Ge Alloys Nano Si/Si-Ge, SKD and III-V composites

Effective Approach to Meet Technical Challenge

- Three separate directions to achieve high ZT values across wide temperature range
  - Optimize high temperature Zintl and rare earth chalcogenides (1275 K – 800 K)
  - Understand and tune "self-assembling" nanostructured TE materials (900 K – 500 K)
  - Nanoscale engineering of high power factor Si, Ge, III-V, skutterudite semiconductors (1275 K – 500 K) K)

- Basic approach is thermal conductivity reduction due to nanoscale grains in bulk with minimum increase in electrical resistivity

Overall Technical Approach

Large scale synthesis of Si, Ge and SiGe nanoparticles

Compaction into dense bulk nanocomposites

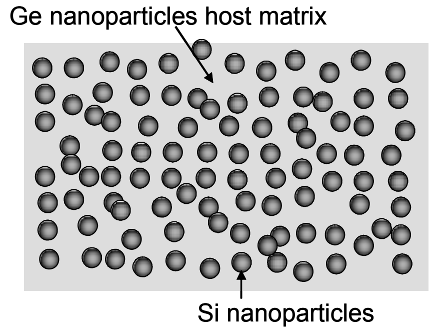
Optimization – particle size distribution, processing conditions, and composition

TE properties and nanostructure measurement

Electron and phonon modeling

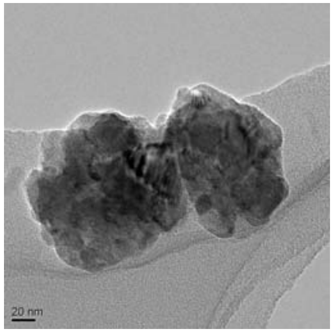
Experimental validation of ZT values

Stability of TE properties and nanocomposites at high temp

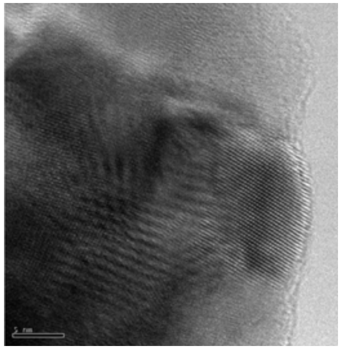


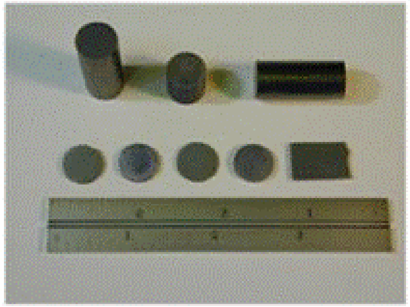
High Energy Ball Milling

$Si_{1-x}Ge_x$ Nanoparticles



Ge Nanoparticles

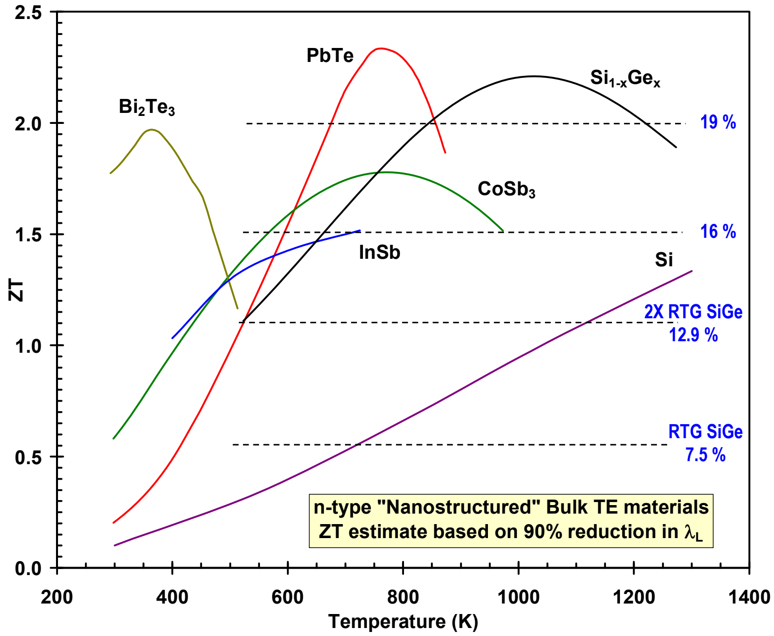




Nano Bulk $Si_{1-x}Ge_x$ and Nanocomposite $Si/Si_{1-x}Ge_x$

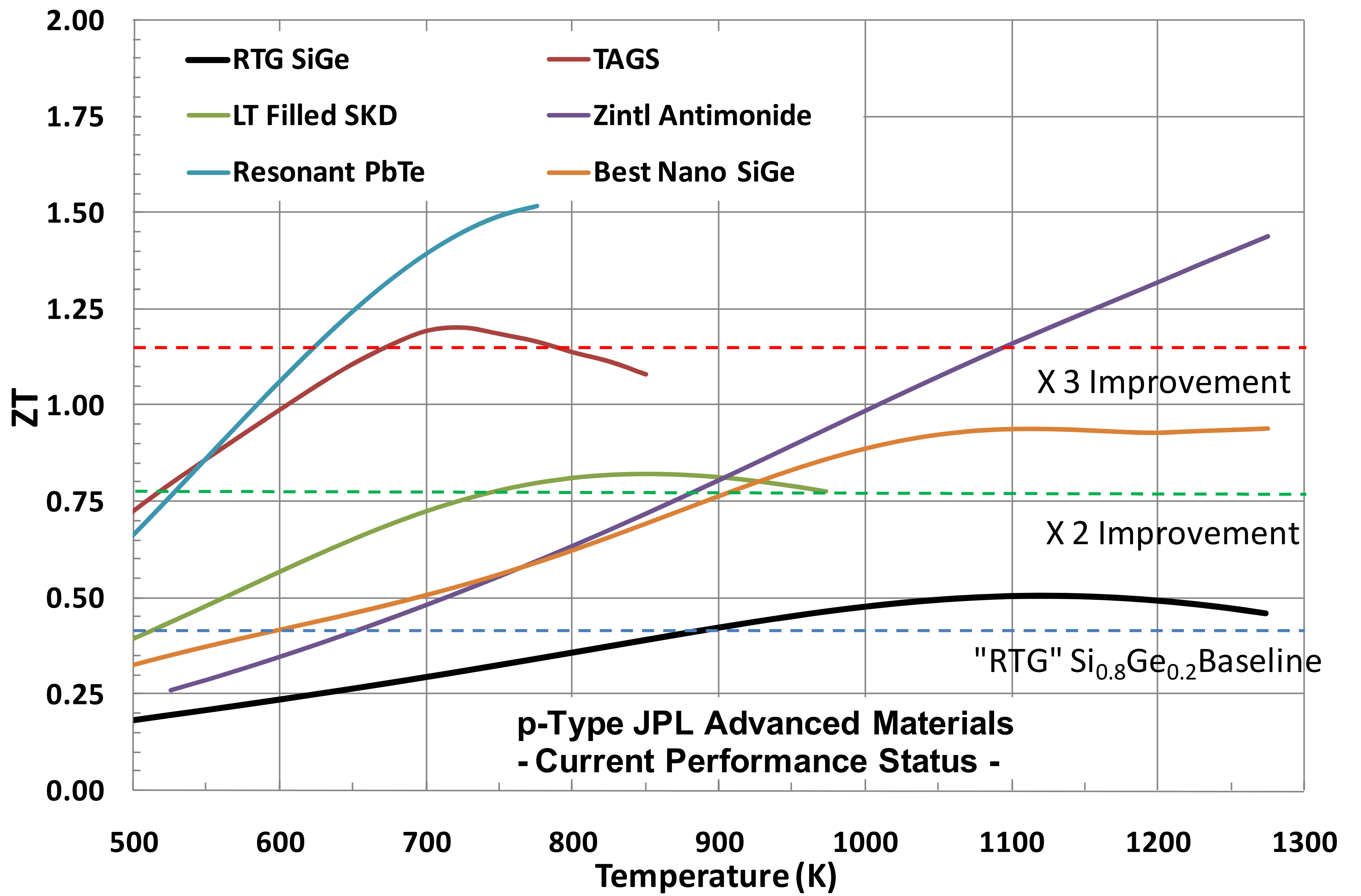
Can We Extend These Results to Other Semiconducting Materials?

- NASA-JPL experiments show that nanostructures reduce thermal conductivity without significantly affecting the electron transport.
  - ***<u>This is a general principle</u>*** for many different materials to improve their ZT.

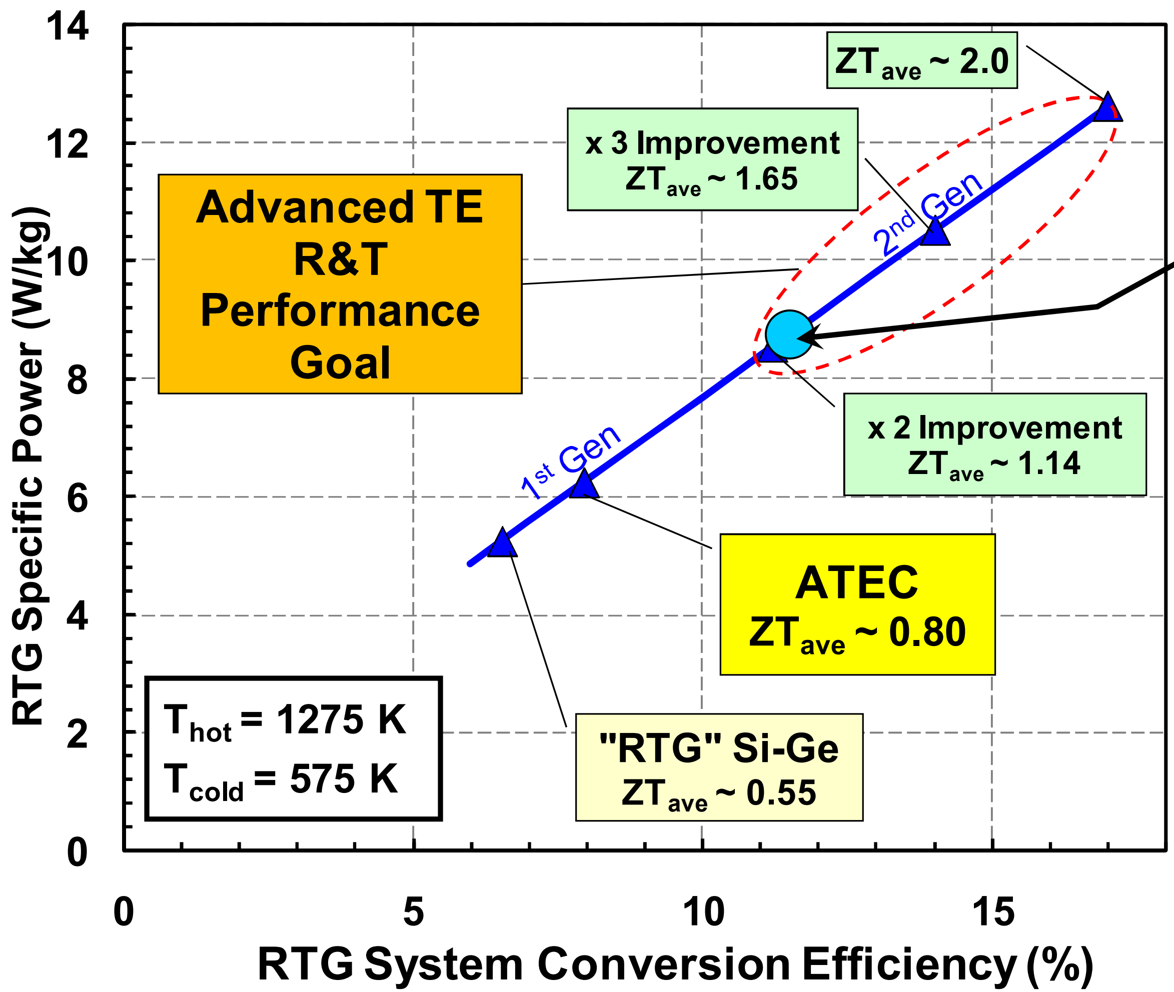


- Work should focus on materials with high power factors and a high thermal conductivities.
  - Examples of candidate materials are $CoSb_3$, PbTe, InSb, and other III-V semiconductors.
  - Peak power factor values as high as 70 μW/(cm·K²) (Compared to ~ 45 μW/(cm·K²) for Si & Si-Ge)
  - ZT_{max} ~ 2 across a wide ΔT could be achieved through segmentation of several TE nanomaterials.

2008 Status on Advanced Bulk TE Materials for Power Generation (p-type)



Advanced TE Research &Technology Program - How Far Are We?



(Based on radiatively coupled vacuum operation unicouple based RTG concept)

Current System Performance Projection using best TE materials in segmented couple configuration

- DOE/NETL Vehicular Thermoelectric Heating, Ventilation and Air Conditioning (HVAC) [October 2008 Start]

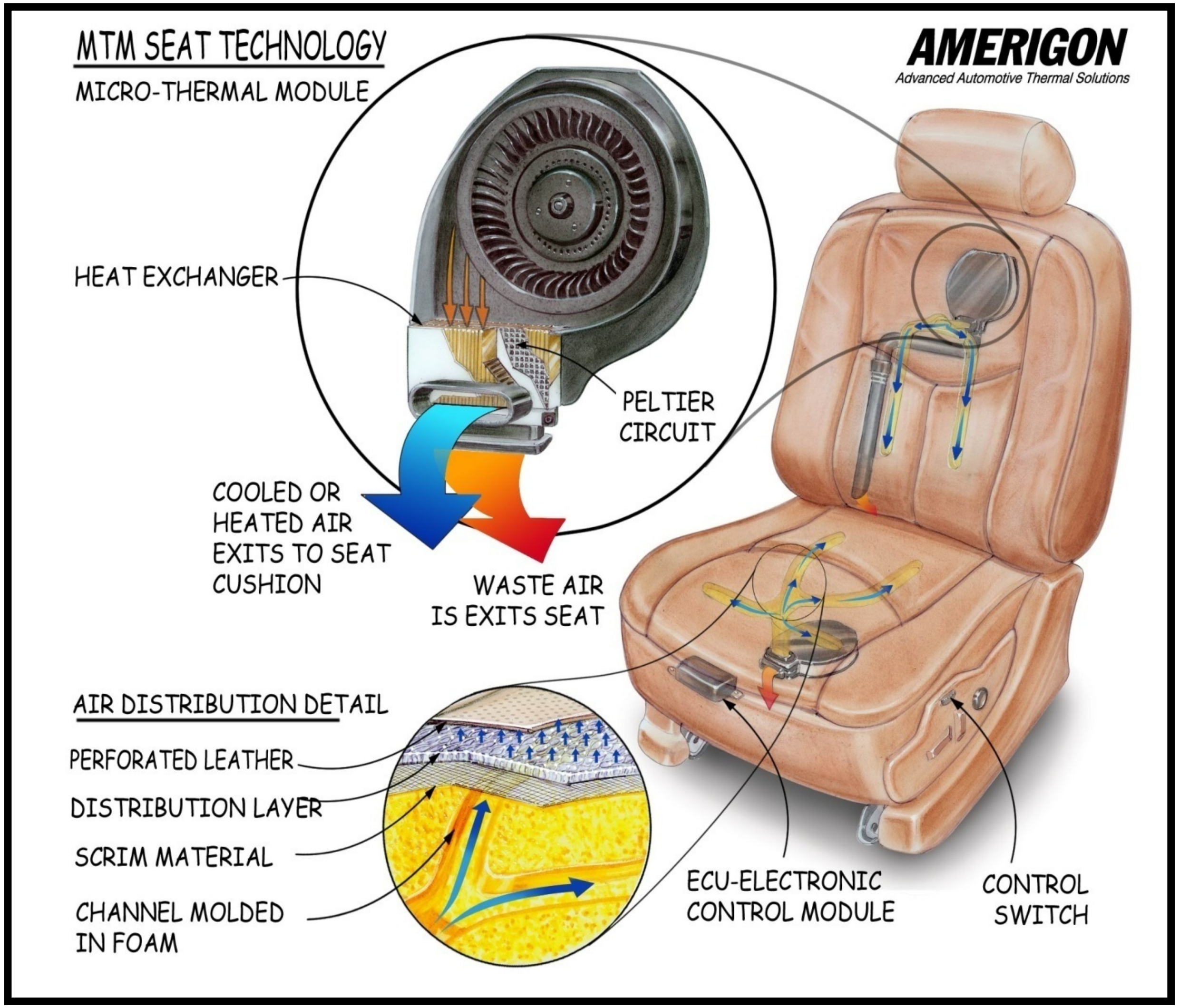
National Impact of Automotive Air Conditioning (A/C)

7 to 8 Billion Gals/fuel used for Automotive A/C

- ~6 % of Light Duty Vehicle Fuel Use
- Current Centralized A/C Systems Require
  - 3.5 to 5 kW
- Zonal or Distributed Thermoelectric Heating, Ventilation and Air Conditioning (HVAC)
  - Requires ~ 670 Watts Cool Driver Only and
    - ~ 2.7 kW Cool 5 Occupants

- Current Vehicular Air Conditioner (A/C) uses Compressed R134-a Refrigerant Gas
  - Vehicles leak 110 g/year R134-a
  - R134-a Has 1300 times the "Greenhouse Gas Effect" as Carbon Dioxide (CO_2)
  - That is 143 kg/year CO_2 equivalent per vehicle/year or
  - 34 Million Metric Tons of CO_2 equivalent/year from personal vehicles in the US from operating air conditioners **Plus** additional R134-a released to atmosphere from accidents and end of life vehicle salvage
- EU is proscribing use of R134-a

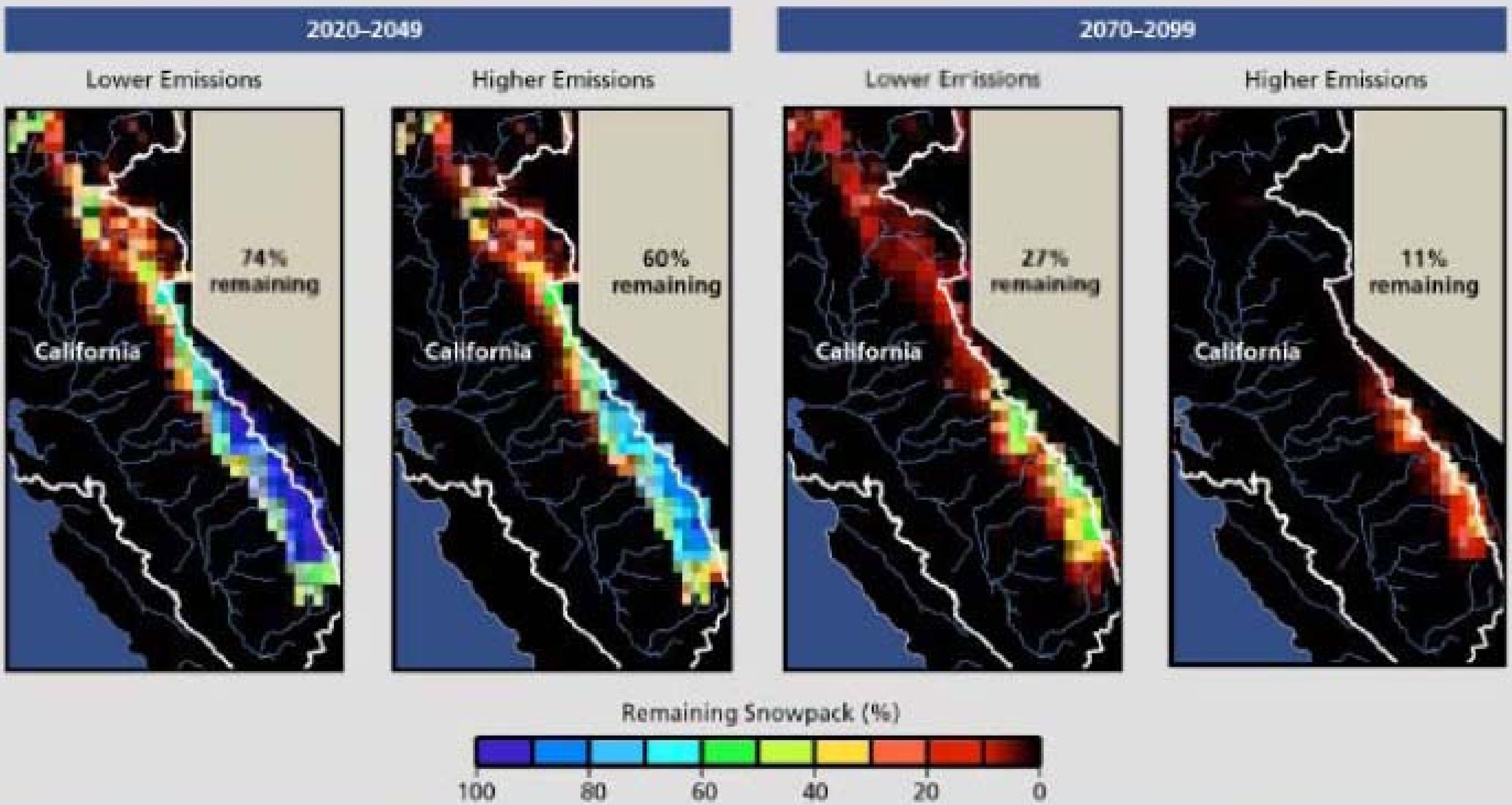
Climate Control Seat™



Zonal HVAC System

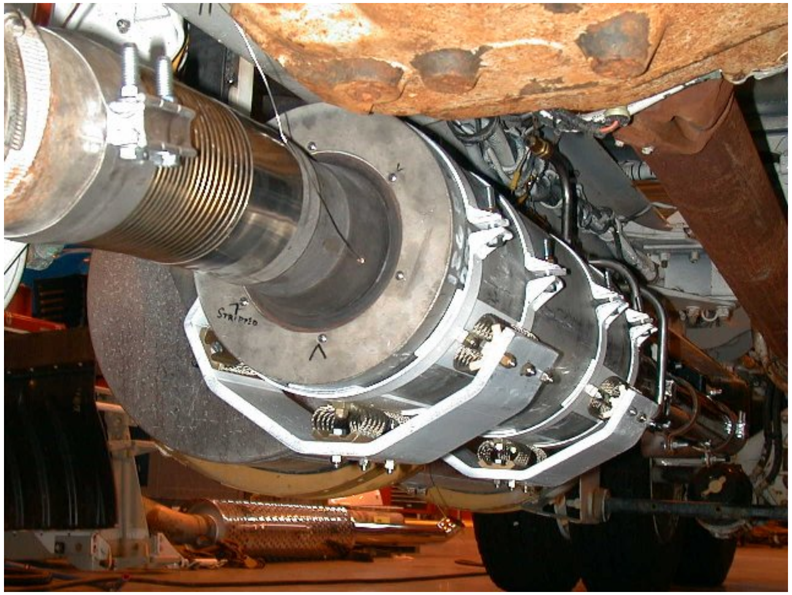
Zonal TE devices located in the dashboard, headliner, A&B pillars and seats/seatbacks

Projections of Sierra snow-pack and implications for water

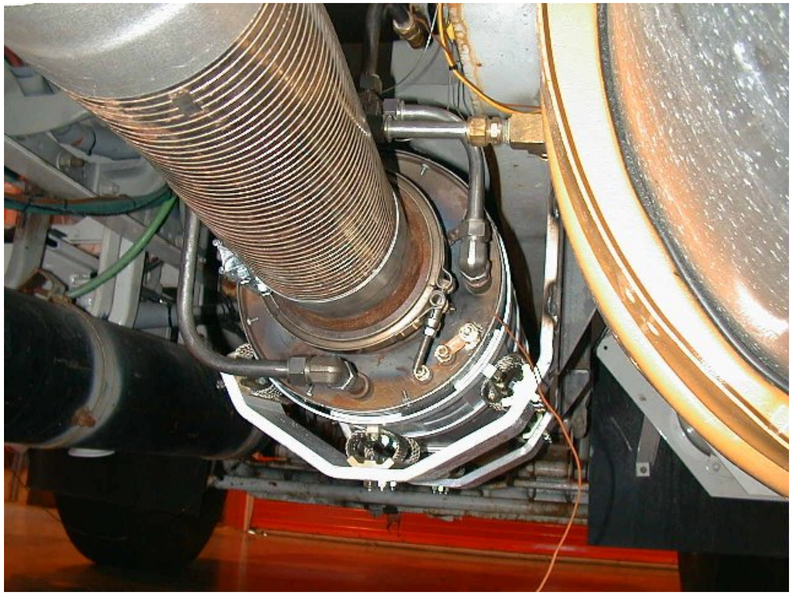


- DOE/NETL Vehicular Thermoeelctric Generator Projects

Installed Thermoelectric Generator on Heavy Duty Truck



Front View



Rear View

Thermoelectric Generator Integrated with Muffler

550,000 Equivalent Miles
PACCAR Test Track

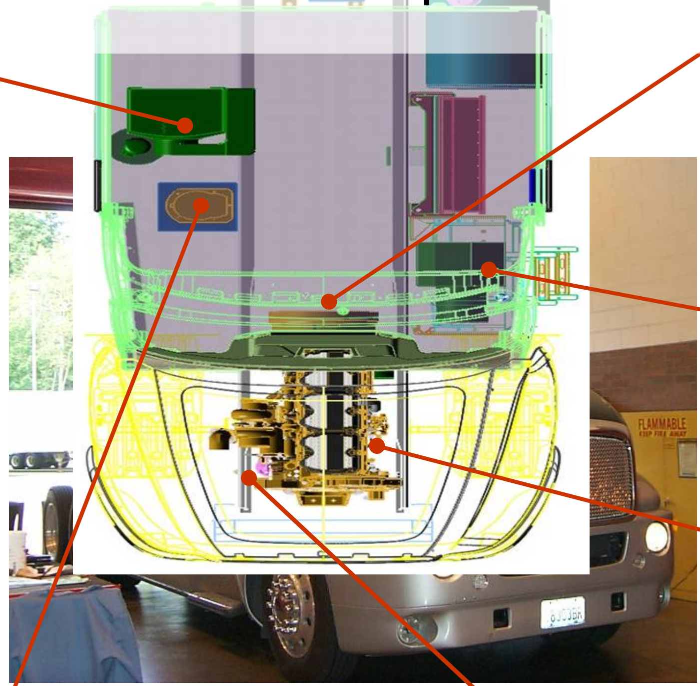
Engine – Caterpillar 3406E, 550 HP
PACCAR's 50 to 1 Test Track
(Note Speed Bumps and Hill)
Standard Test Protocols Used or Each Evaluation
Heavy Loaded (over 75,000 lbs)
TEG Installed Under the Cabin

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Beltless or More Electric Engine

Truck Electrification

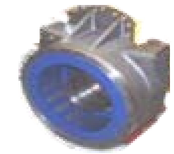
Electrify accessories
decouple them from engine
Match power demand to real time need
Enable use of alternative power sources



Modular HVAC

Variable speed compressor more efficient and serviceable 3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

Starter Generator Motor

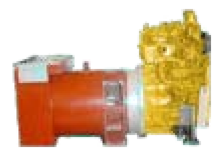


Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

Shore Power and Inverter

Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power

Auxiliary Power Unit



Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

Down Converter

Supplies 12 V Battery from DC Bus

Compressed Air Module

Supplies compressed air for brakes and ride control

Electric Water Pump

Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

Electric Oil Pump

Variable speed
Higher efficiency

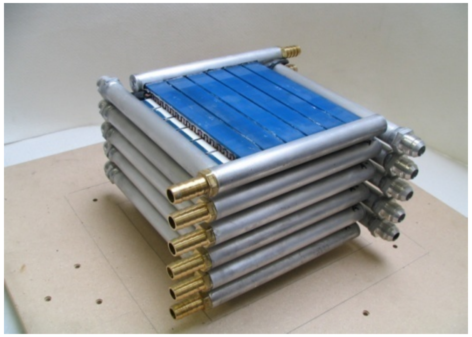
Competitive Award Selections

(March 2004 RFP)

Awardees	Additional Team Members
High Efficiency Thermoelectric	
General Motor Corporation General Electric	, University of Michigan, University of South Florida, Oak Ridge National Laboratory, and Marlow Industries
BSST, LLC.	Visteon, BMW-NA, Ford, Marlow Industries
Michigan State University	NASA Jet Propulsion Laboratory Cummins Engine Company Tellurex, Iowa State

BSST Thermoelectric Waste Heat Recovery Program

- BSST is leading a team including BMW, Visteon and Ford
- Waste heat recovery heat exchangers, TEG and power conversion electronics were built and bench tested
- Computer simulation has shown 8% fuel efficiency increase (MY 2006 530i with electrical load of 750W)
- Currently doing system integration and bench test
- Engine dynamometer testing in Q1 Fy'09



BSST innovative solutions in temperature control

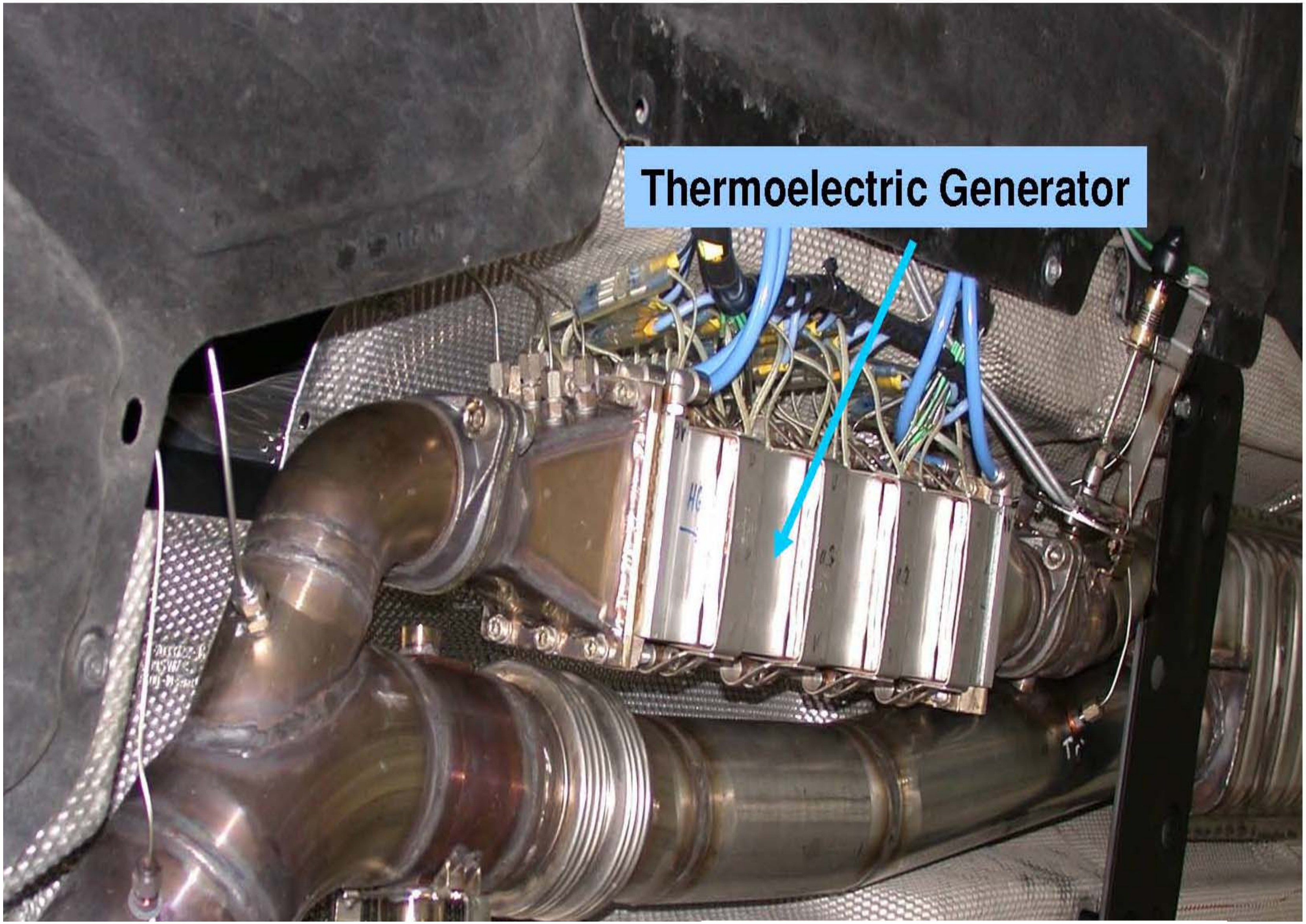
BMW

Visteon

NETL

California Institute of Technology 1891

TEG Installed in BMW Series 5 Test Vehicle



TEG Location in BMW Series 5

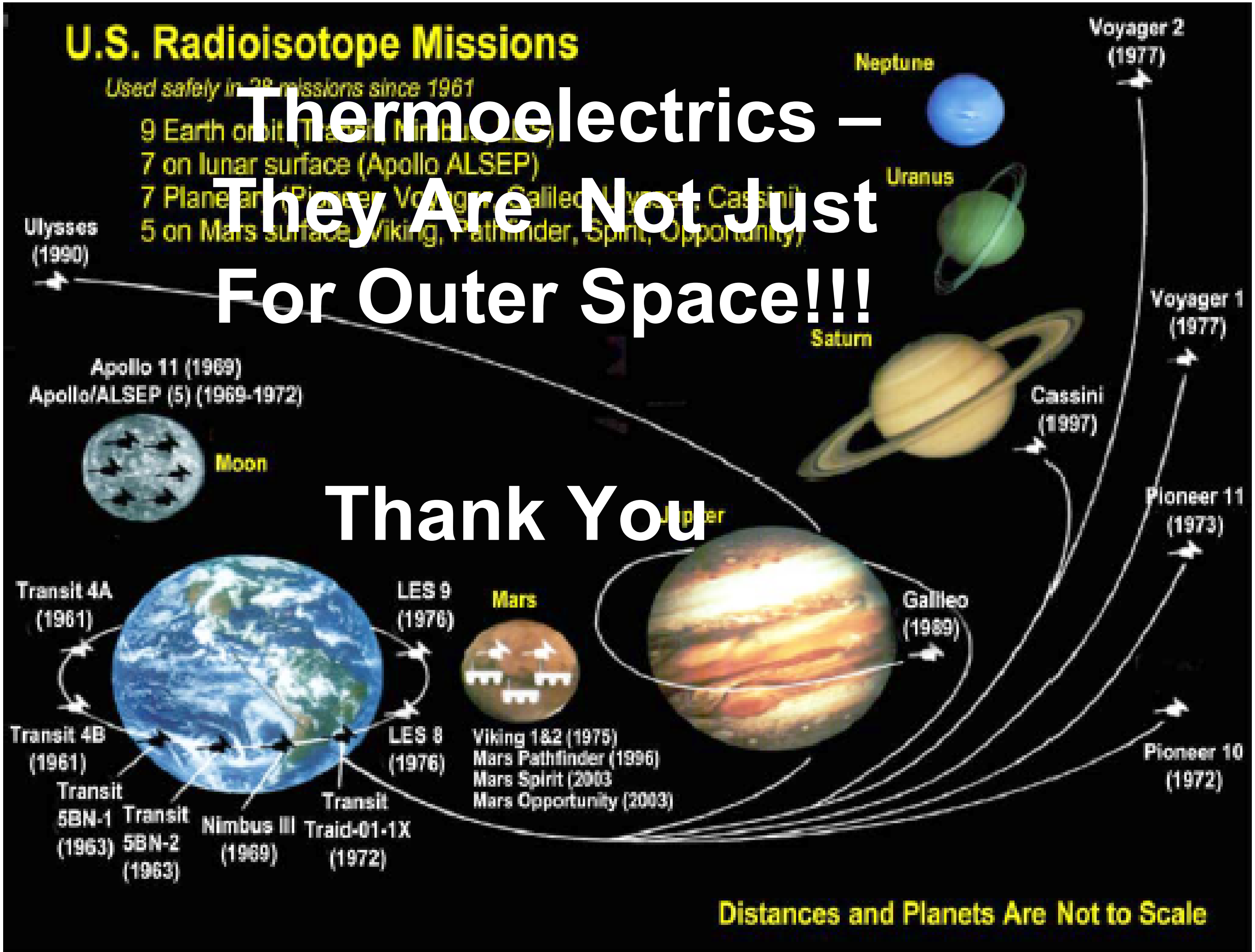
BSST/BMW TEG Test Instrumentation

First Generation Thermoelectric Generator Project Goals

- Produce a Nominal 10 % Improvement in Fuel Economy without Increasing Emissions
- Prove Commercial Viability

- Thermoelectric Generator Parameters
- Power Output : Highway ~ 1kW , City ~500 W
- ZT (average) Module ~ 1.0
- Temperature difference ~ 250oC – 390oC
- Thermoelectric Efficiency ~12%
- Weight <100lbs
- Cost installed > $1.0/watt

Thermoelectrics – They Are Not Just For Outer Space!!!



Thank You