Sustainable TRANSPORTATION

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Automotive Thermoelectric Generators and HVAC

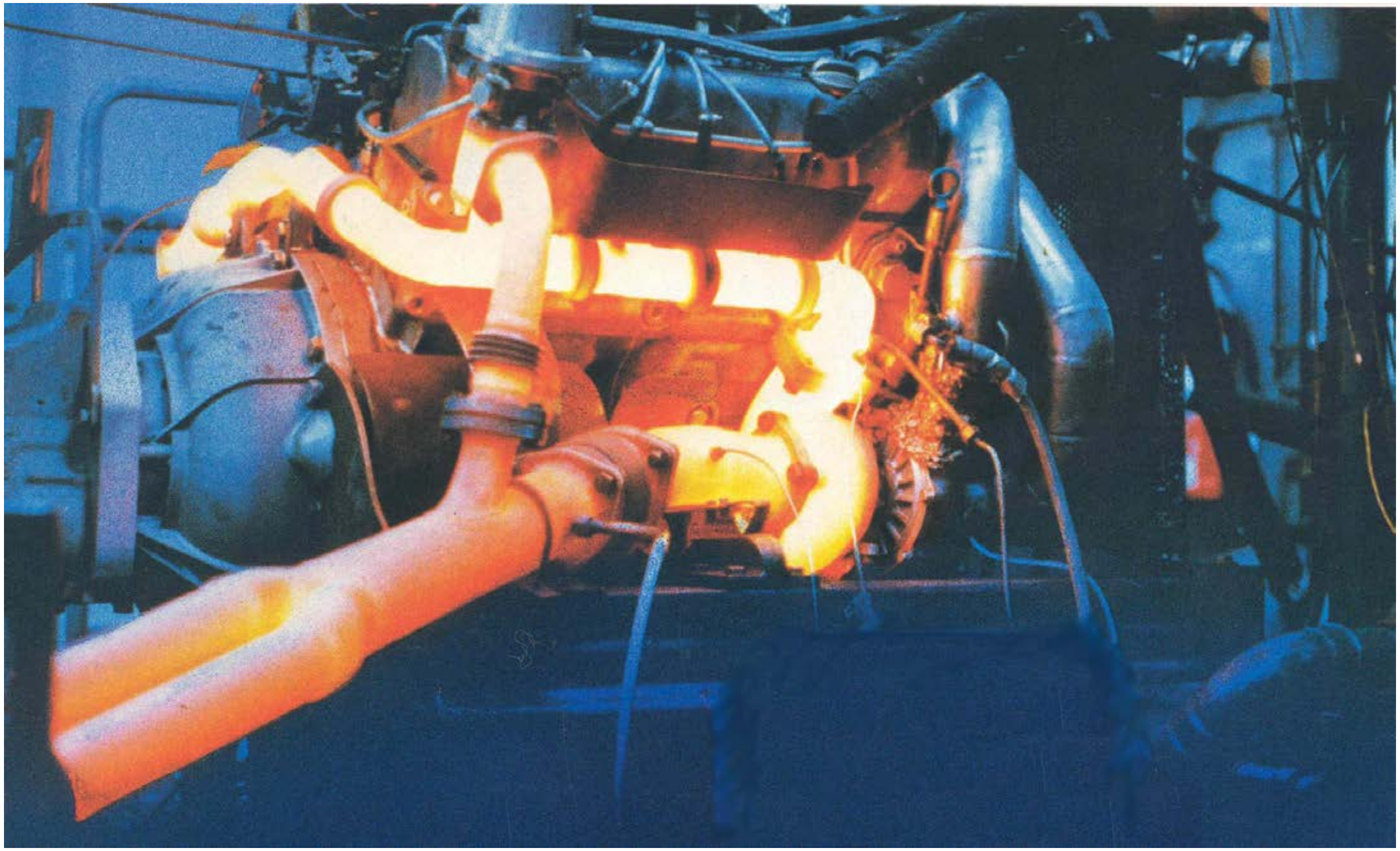
John Fairbanks
Solid State Energy Conversion
Advanced Combustion Engine R&D Program
Vehicle Technologies Office

2013 Annual Merit Review and Peer Evaluation Meeting
DOE Vehicle Technologies Office
Washington, DC
May 17, 2013

ACE00E

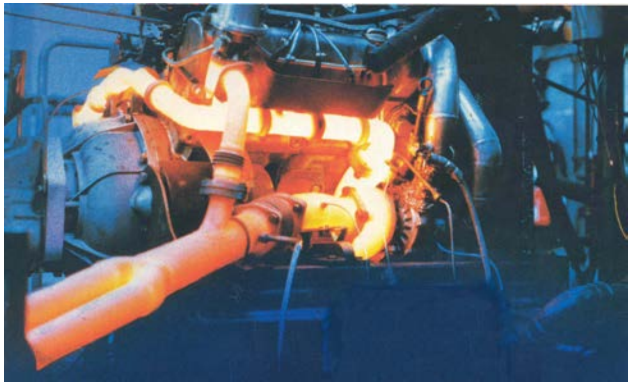
Vehicular Engine Waste Heat Energy

Opportunity for improving fuel economy arises from high temperature of vehicle exhaust systems: converting heat to electricity reduces load on engine (electricity powers components; smaller alternator needed)



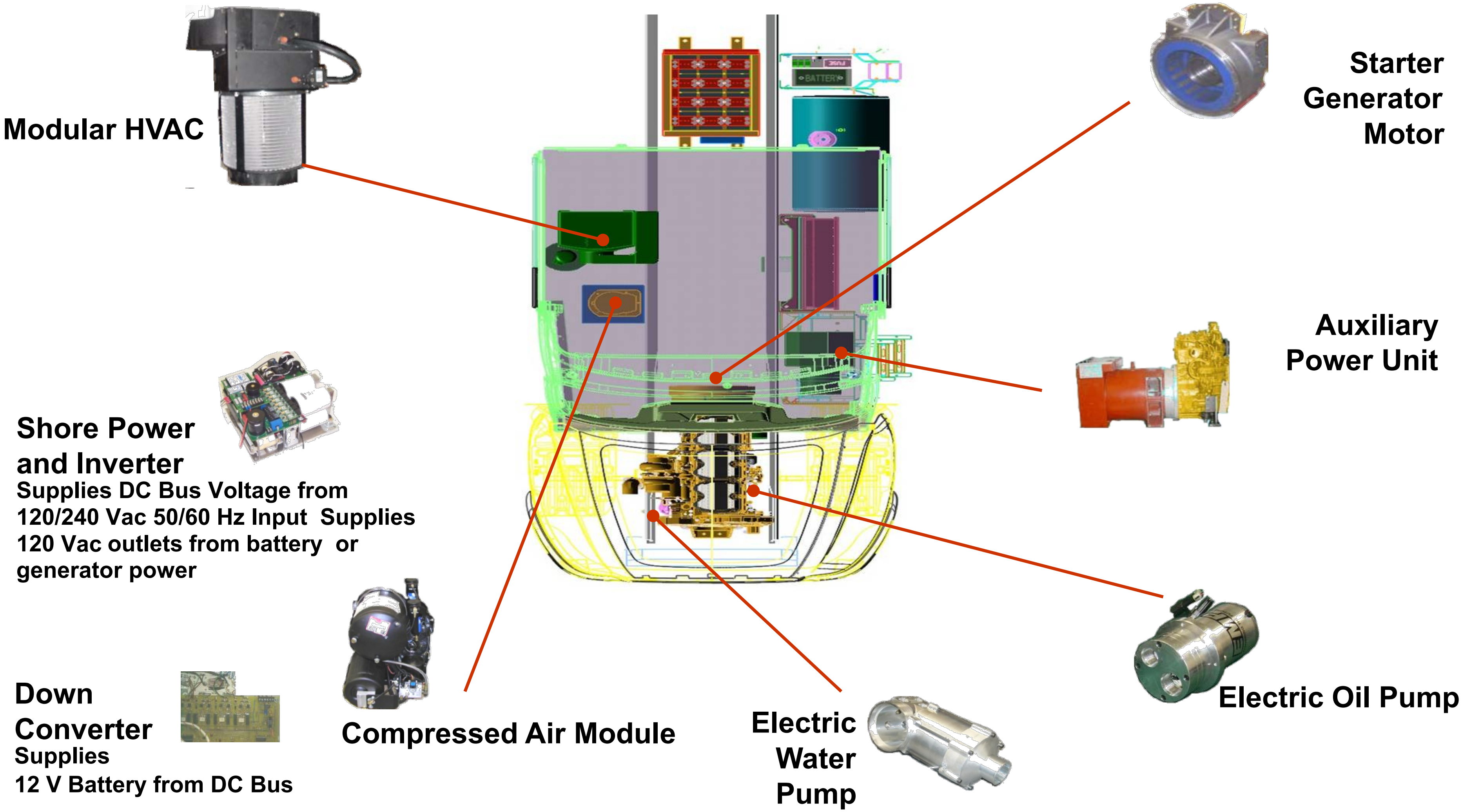
Vehicular Engine Waste Heat Energy Recovery

- **Goal:** integrate vehicles with a technology that will improve fuel economy
- **Approach:** use thermoelectrics to convert energy in hot engine exhaust directly to electricity



- **Target:** > 5% improvement in fuel economy; achieved by using output of TEG to power key electrical components

Fuel economy is improved when belt-driven accessories are replaced with electric motor drives powered by Thermoelectrics



Toward the beltless engine

Experimental Assessment of Potential of TEG to Improve Fuel Economy (GMZ Energy)

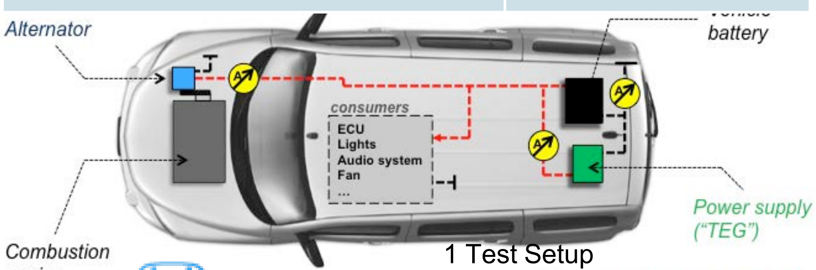
Up 3.45% Fuel Economy Improvement potential with alternator removal in 2.0L Engine

[1]*Fuel economy improvements tested with no back pressure or weight considerations of a thermoelectric generator over US06 Cycle for Chevy HHR

Constant Supplemental Power to Engine (W)	Fuel Economy gain [%]
480	**+ 2.94***

[1+]Fuel economy improvements tested with no alternator attached to engine. All power supplied to HHR by external power supply. Tested over US06 Cycle

Supplemental Power to Engine (W)	Fuel Economy gain [%]
As needed	**+ 3.45[+]**



1 Test Setup

Off cycle credit granted of 2.9%[*4] and HWFET Cycle Fuel Economy Gain of 4.07%[+]

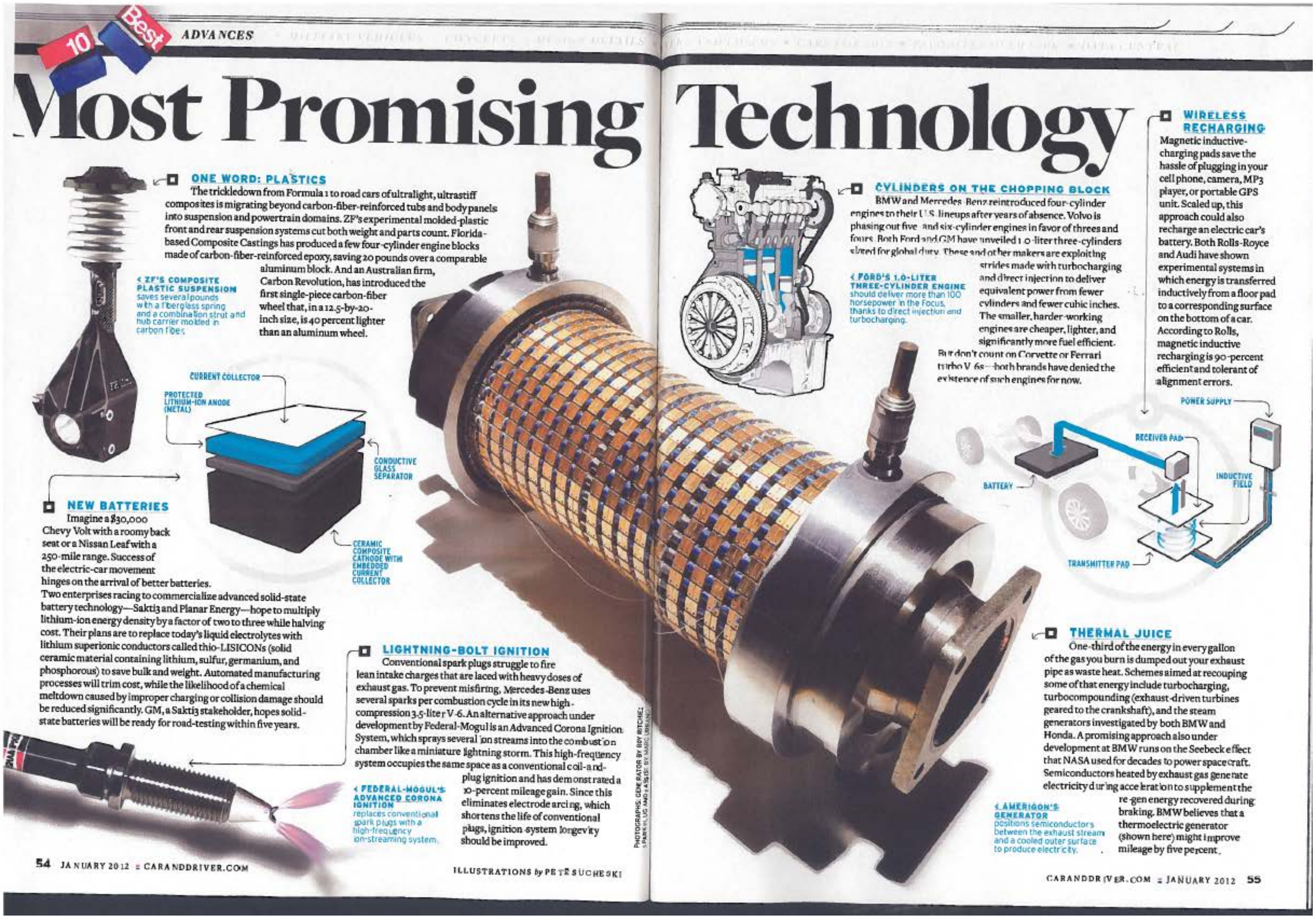
- Credit granted by 132W power generation : 0.5% [*2*3]
- Credit granted by quick engine warm up : 0.9% [*3*4]
- Credit granted by quick transmission warm up using exhaust heat : 0.9% [*3*4]
- Credit granted by installation of device encouraging cabin heating to vehicle having idle start/stop function :0.6% [*3*4]

*2 Power Generation based on average output power of TEG over 5 cycle
*3 Credits based on fuel economy regulations of 2025
*4 2.9% Fuel economy improvement based on a cold start from Cold FTP Cycle

Supplemental Power to Engine (W)	Fuel consumption [mpg]	Delta to baseline [%]
Baseline, 0 W	39.67	-
"TEG", max. 330 W	40.85	**+ 2.97[+]**
"TEG", max. 480 W	41.28	**+ 4.07[+]**

[+]Fuel economy improvements tested with no back pressure or weight considerations of a thermoelectric generator

Car and Driver "Most Promising Technology," January 2012



ADVANCES

10 Best

Most Promising Technology

ONE WORD: PLASTICS

The trickledown from Formula 1 to road cars of ultralight, ultrastiff composites is migrating beyond carbon-fiber-reinforced tubs and body panels into suspension and powertrain domains. ZF's experimental molded-plastic front and rear suspension systems cut both weight and parts count. Florida-based Composite Castings has produced a few four-cylinder engine blocks made of carbon-fiber-reinforced epoxy, saving 20 pounds over a comparable aluminum block. And an Australian firm, Carbon Revolution, has introduced the first single-piece carbon-fiber wheel that, in a 12.5-by-20-inch size, is 40 percent lighter than an aluminum wheel.

ZF'S COMPOSITE PLASTIC SUSPENSION saves several pounds with a fiberglass spring and a combination strut and hub carrier molded in carbon fiber.

NEW BATTERIES

Imagine a $30,000 Chevy Volt with a roomy back seat or a Nissan Leaf with a 250-mile range. Success of the electric-car movement hinges on the arrival of better batteries. Two enterprises racing to commercialize advanced solid-state battery technology—Sakti3 and Planar Energy—hope to multiply lithium-ion energy density by a factor of two to three while halving cost. Their plans are to replace today's liquid electrolytes with lithium superionic conductors called thio-LISICONs (solid ceramic material containing lithium, sulfur, germanium, and phosphorous) to save bulk and weight. Automated manufacturing processes will trim cost, while the likelihood of a chemical meltdown caused by improper charging or collision damage should be reduced significantly. GM, a Sakti3 stakeholder, hopes solid-state batteries will be ready for road-testing within five years.

LIGHTNING-BOLT IGNITION

Conventional spark plugs struggle to fire lean intake charges that are laced with heavy doses of exhaust gas. To prevent misfiring, Mercedes-Benz uses several sparks per combustion cycle in its new high-compression 3.5-liter V-6. An alternative approach under development by Federal-Mogul is an Advanced Corona Ignition System, which sprays several ion streams into the combustion chamber like a miniature lightning storm. This high-frequency system occupies the same space as a conventional coil-and-plug ignition and has demonstrated a 10-percent mileage gain. Since this eliminates electrode arcing, which shortens the life of conventional plugs, ignition-system longevity should be improved.

FEDERAL-MOGUL'S ADVANCED CORONA IGNITION replaces conventional spark plugs with a high-frequency ion-streaming system.

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ILLUSTRATIONS by PETE SUCHESKI

PHOTOGRAPHS: GENERATOR BY ROY RITCHIE; SPARK PLUG AND ASSIST BY MARC URBANO

CYLINDERS ON THE CHOPPING BLOCK

BMW and Mercedes-Benz reintroduced four-cylinder engines to their U.S. lineups after years of absence. Volvo is phasing out five- and six-cylinder engines in favor of threes and fours. Both Ford and GM have unveiled 1.0-liter three-cylinders slated for global duty. These and other makers are exploiting strides made with turbocharging and direct injection to deliver equivalent power from fewer cylinders and fewer cubic inches. The smaller, harder-working engines are cheaper, lighter, and significantly more fuel efficient. But don't count on Corvette or Ferrari turbo V-6s—both brands have denied the existence of such engines for now.

FORD'S 1.0-LITER THREE-CYLINDER ENGINE should deliver more than 100 horsepower in the Focus, thanks to direct injection and turbocharging.

WIRELESS RECHARGING

Magnetic inductive-charging pads save the hassle of plugging in your cell phone, camera, MP3 player, or portable GPS unit. Scaled up, this approach could also recharge an electric car's battery. Both Rolls-Royce and Audi have shown experimental systems in which energy is transferred inductively from a floor pad to a corresponding surface on the bottom of a car. According to Rolls, magnetic inductive recharging is 90-percent efficient and tolerant of alignment errors.

THERMAL JUICE

One-third of the energy in every gallon of the gas you burn is dumped out your exhaust pipe as waste heat. Schemes aimed at recouping some of that energy include turbocharging, turbocompounding (exhaust-driven turbines geared to the crankshaft), and the steam generators investigated by both BMW and Honda. A promising approach also under development at BMW runs on the Seebeck effect that NASA used for decades to power spacecraft. Semiconductors heated by exhaust gas generate electricity during acceleration to supplement the re-gen energy recovered during braking. BMW believes that a thermoelectric generator (shown here) might improve mileage by five percent.

AMERIGON'S GENERATOR positions semiconductors between the exhaust stream and a cooled outer surface to produce electricity.

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The power of increasing fuel economy by 1% and 5%

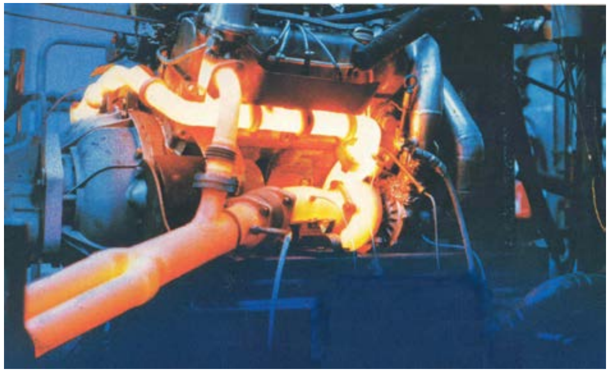
	Segment	Type of Savings	Estimated Fuel Savings over 1 Year (Billion nominal US Dollars)
Auto/Light-duty trucks	Personal	1% Fuel Savings	$5.0 B
Heavy-duty trucks	Commercial	1% Fuel Savings	$1.4 B
Auto/Light-duty trucks	Personal	5% Fuel Savings	$25 B
Heavy-duty trucks	Commercial	5% Fuel Savings	$6.9B

Reference: Davis (2012), Transportation Energy Data Book, Table 1.17. EIA (2013), "Gasoline and Diesel Fuel Update" (http://www.eia.gov/petroleum/gasdiesel/ accessed March 2013)

TEG contribution to Future CAFE

- White House announced an agreement with 13 major automakers to achieve 54.5 mpg by 2025

- Recovering engine exhaust waste heat using thermoelectric generators (TEGs) is consistent with this objective



World Wide Funding of Thermoelectrics
compiled by Gentherm (J. LaGrandeur)

- GM
- Ford
- BMW
- Honda
- Daimler Benz
- Volkswagon
- Fiat/Chrysler
- Renault
- Toyota

Global Investment in TE Technology- November 2012 Snapshot (~ 4 yr bucket)		
Region	**Total Spent, USD**	**Total Government funds, USD**
EU	$ 145,732,370	$ 97,336,809
North America	$ 53,923,077	$ 37,250,000
Russia	$ 40,000,000	$ 20,000,000
Japan	$ 22,600,000	$ 21,700,000
China	$ 15,100,000	$ 15,100,000
Worldwide Total	**$ 277,355,447**	**$ 191,386,809**

Thermoelectric Funding Partners

- California Energy Commission
- U.S. Army Tank, Automotive, Research, Development and Engineering Center (TARDEC)
- National Science Foundation

<u>Program of R&D with Industrial and Academic Partners</u>

Lead Industrial Organizations:

Ford, GM, GenTherm, GMZ Energy, *BMW*

Lead Academic Organizations:

Ohio State*, Purdue,* ***Stanford,*** *SUNY-Stony Brook, TAMU, UCLA, UT-Austin, VT*

R&D Project Presentations

Lead Industrial Organizations (reviewed)

Ford, GM, GenTherm, GMZ Energy, *BWM*

Ford: "Thermoelectric HVAC and Thermal Comfort Enablers for Light-Duty Vehicle Applications", Clay Maranville

GM: "Energy Efficient HVAC Systems for Distributed Cooling/Heating with Thermoelectric Devices", Jeffrey Bozeman

GenTherm: "Thermoelectric Waste Heat Recovery Program for Passenger Vehicles", Doug Crane

GM: "Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power", Jim Salvadore

GMZ: "Nanostructured High-Temperature Bulk Thermoelectric Energy Conversion for Efficient Automotive Waste Heat Recovery", Jonathan D'Angelo

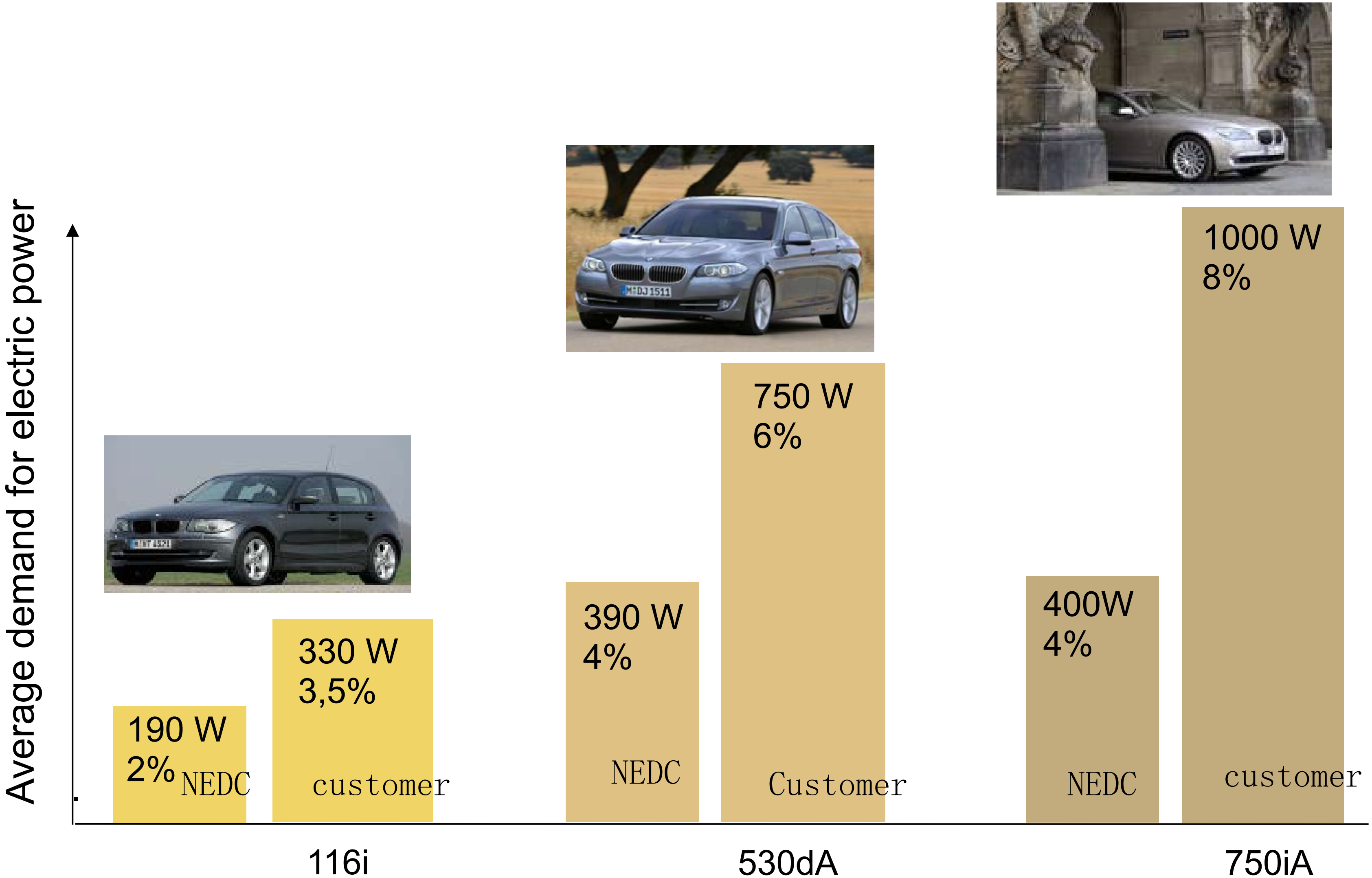
Lead Academic Organizations: (not reviewed)

Ohio State*, Purdue,* ***Stanford,*** *SUNY-Stony Brook, TAMU, UCLA, UT-Austin, VT*

Stanford: "Automotive Thermoelectric Modules with Scalable Thermo and Electrical-Mechanical Interfaces", Kenneth Goodson

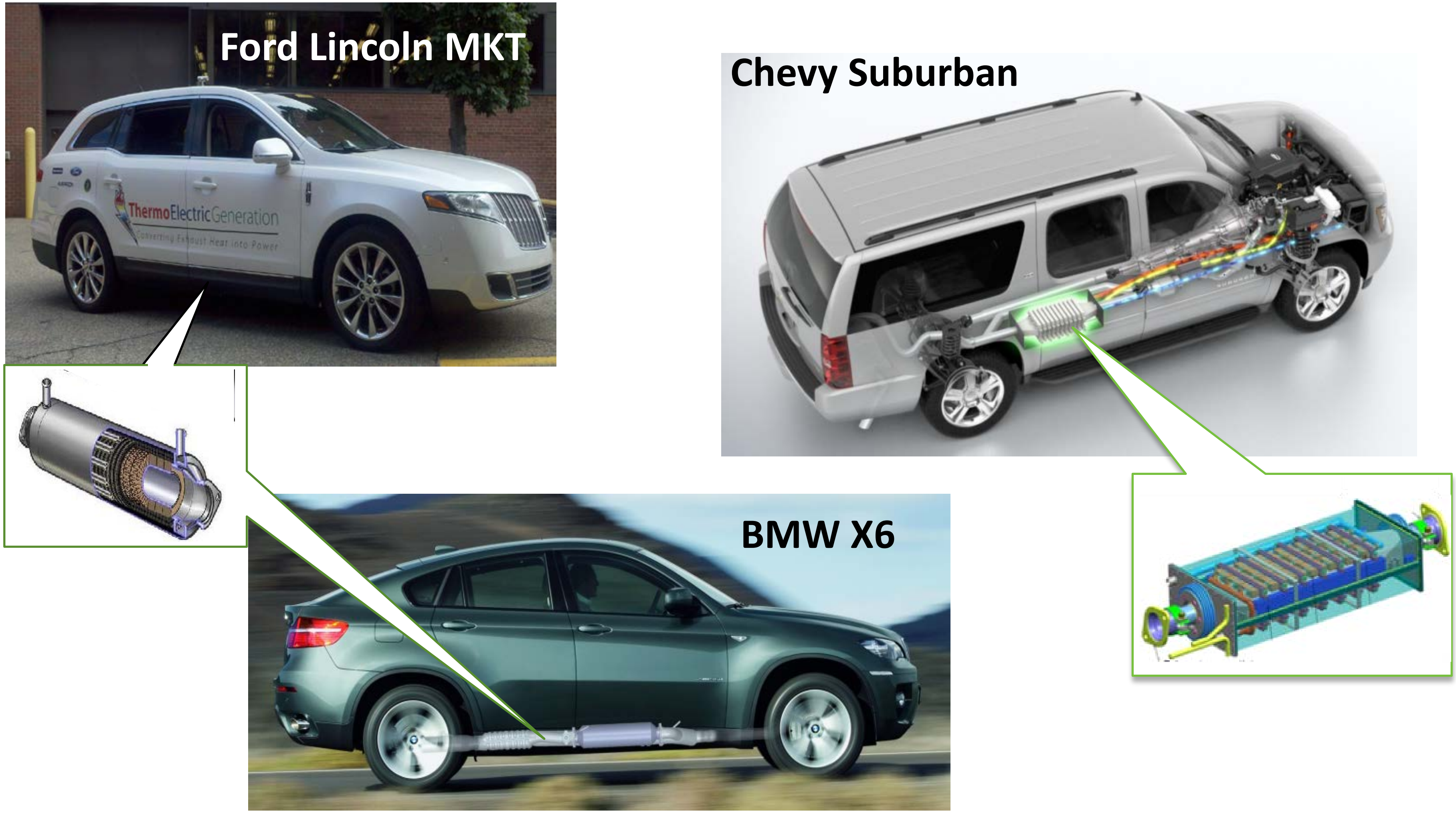
Ohio State University: "SEEBECK Saving Energy Effectively by Engaging in Collaborative Research and Sharing Knowledge", Joseph Heremans

Thermoelectric Power Generation –
BMW's and VTO's Projections for BMW Sedans

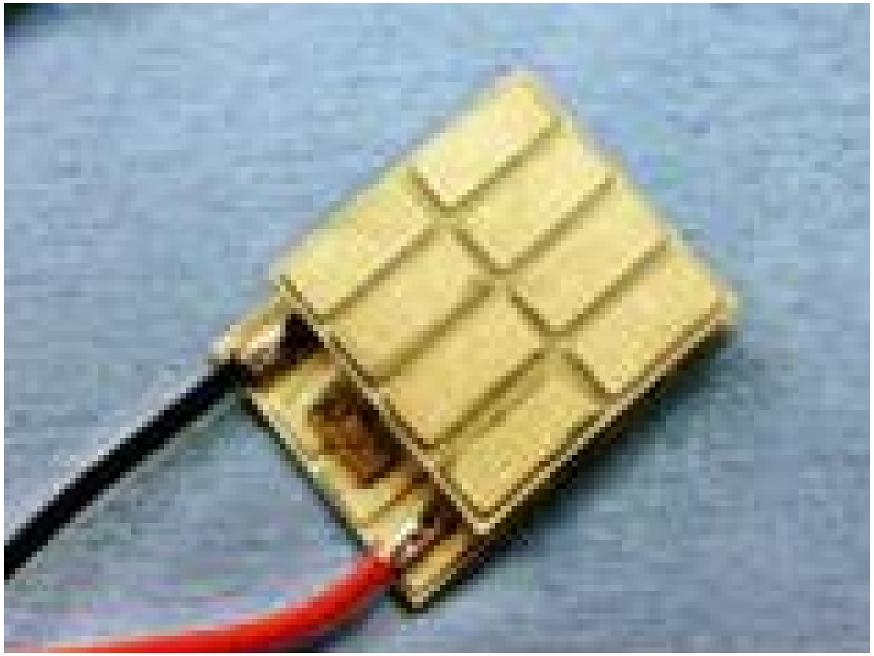


Source: BMW Group

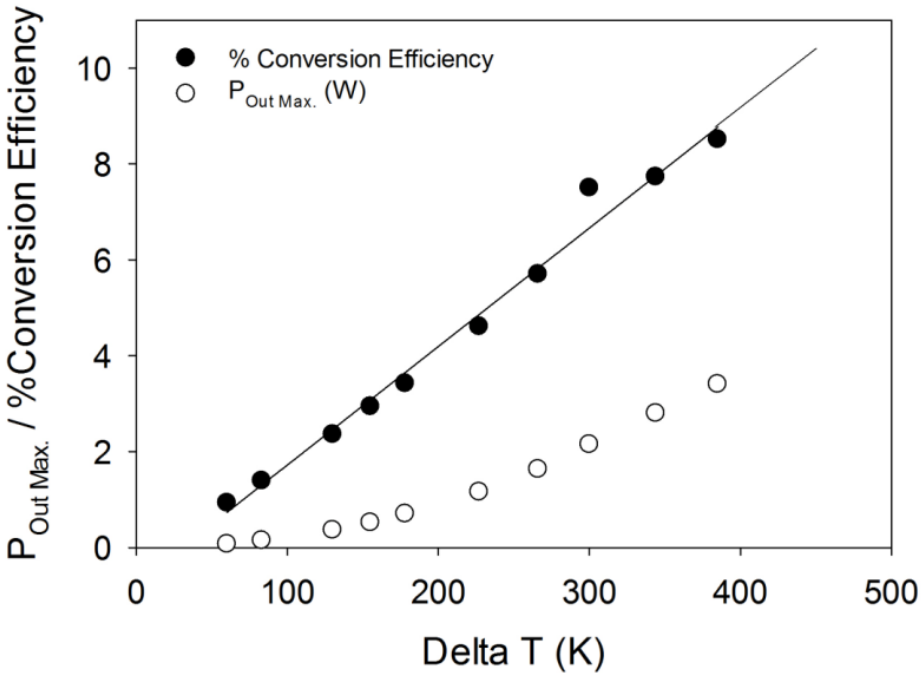
Vehicle Integration with Thermoelectics: FORD, GM and BMW
Prototype integration pursued under DOE/industry sponsorship



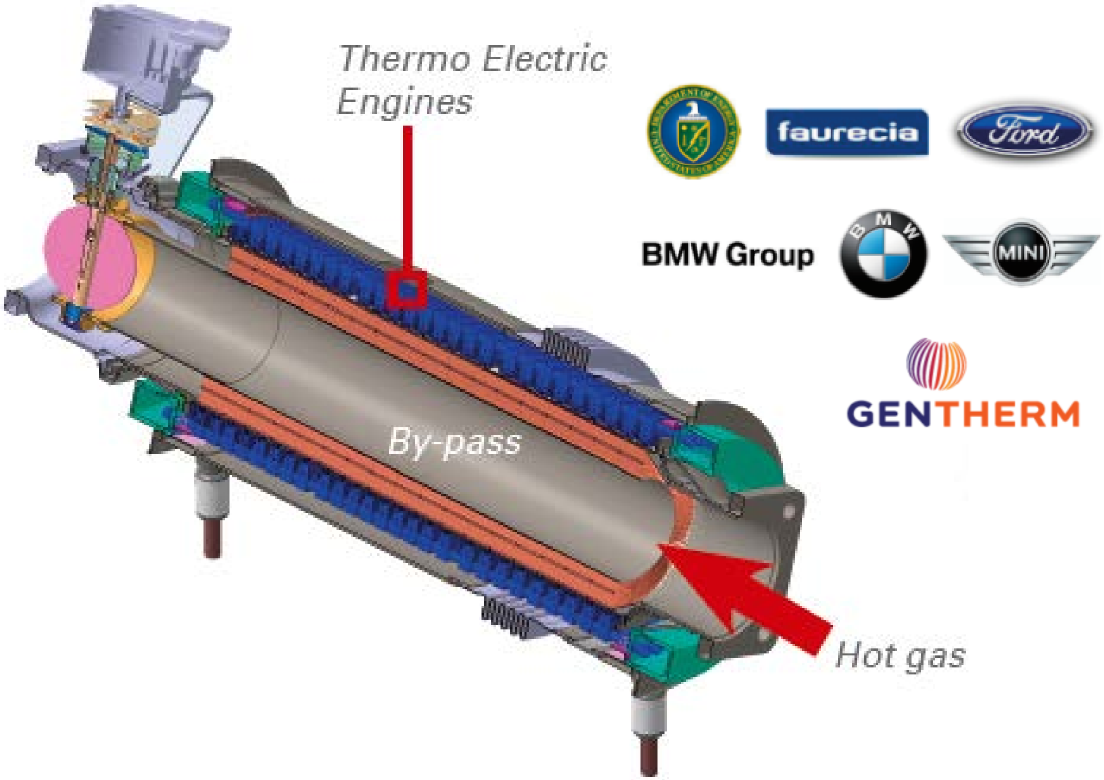
GM TEG Design and Performance with Gen 2 Skutterudite Modules



10% conversion efficiency with ΔT=450K.

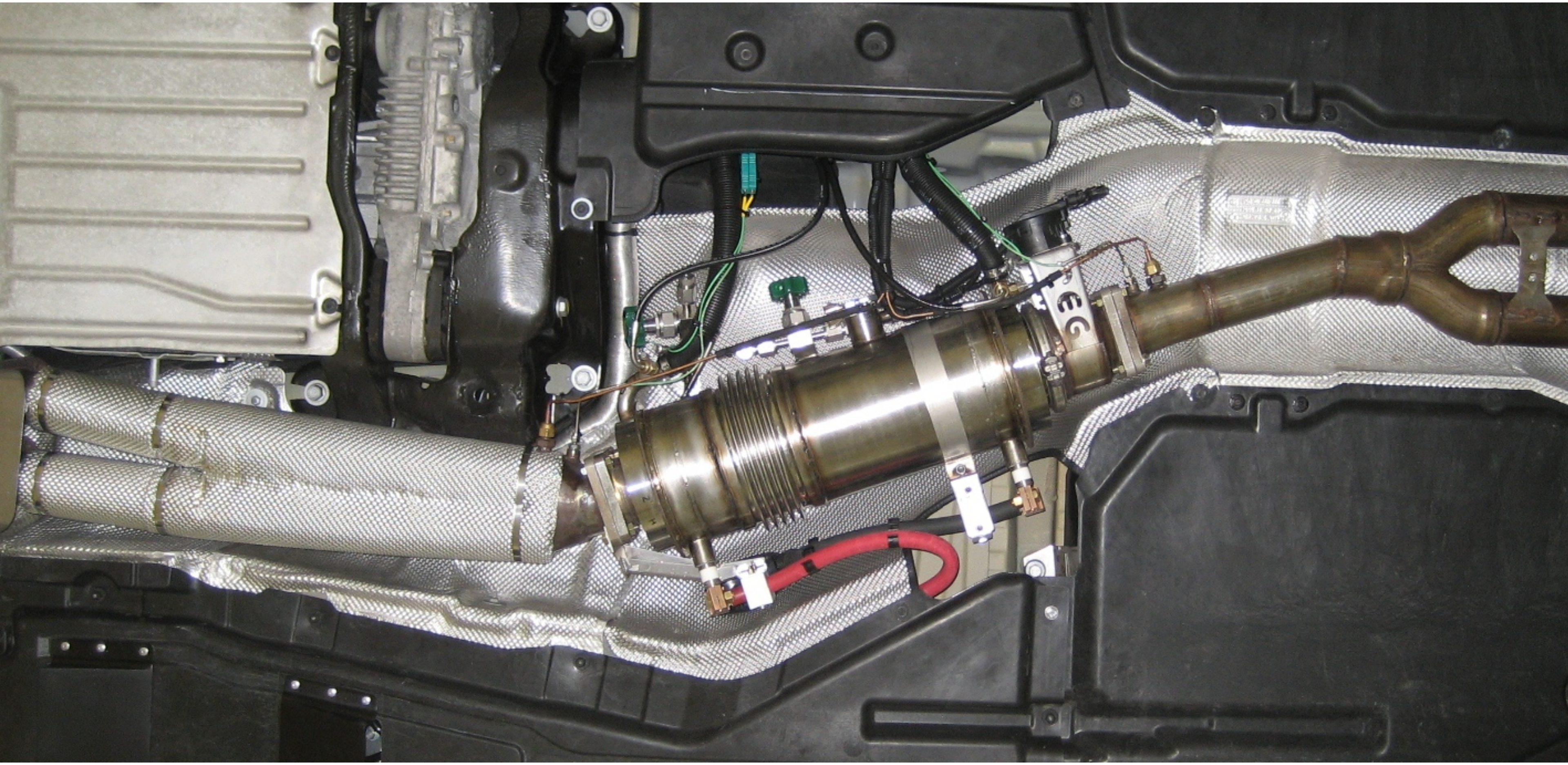


GenTherm/Ford/BMW/Faurecia Cylindrical TEG



Cylindrical TEG design well suited for exhaust system

TEG Installation in BMW X6

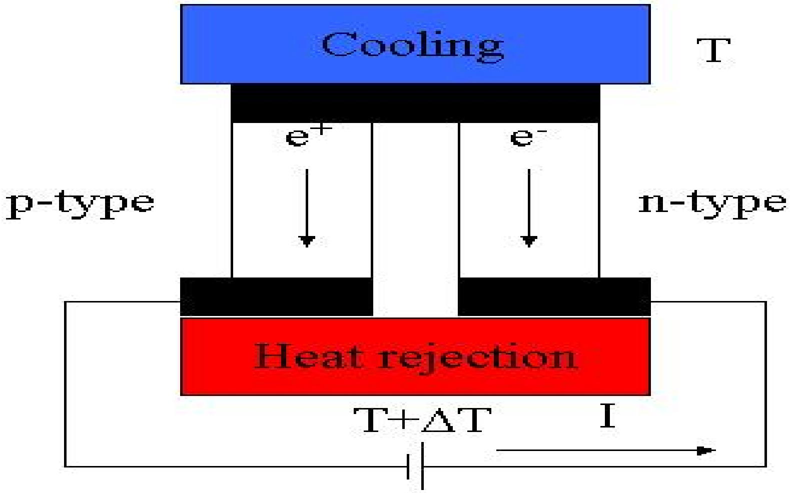


Research in academia pursued under 2010 Solicitation "NSF/DOE Partnership on Thermoelectric Devices for Vehicle Applications" (see NSF 10-549)

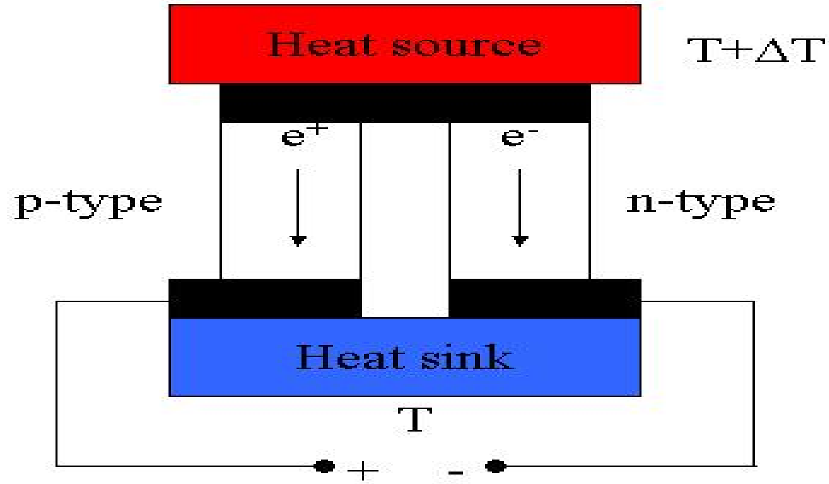
Vehicle Technologies Office (EERE)

Thermal Transport Processes Program (Engineering Directorate)

Much of effort directed toward material development ("ZT")



HVAC



Power Generation

$$\eta = \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_C/T_H}\right)$$

$$ZT = \frac{\sigma\alpha^2}{(\kappa_e + \kappa_L)} \bullet T$$

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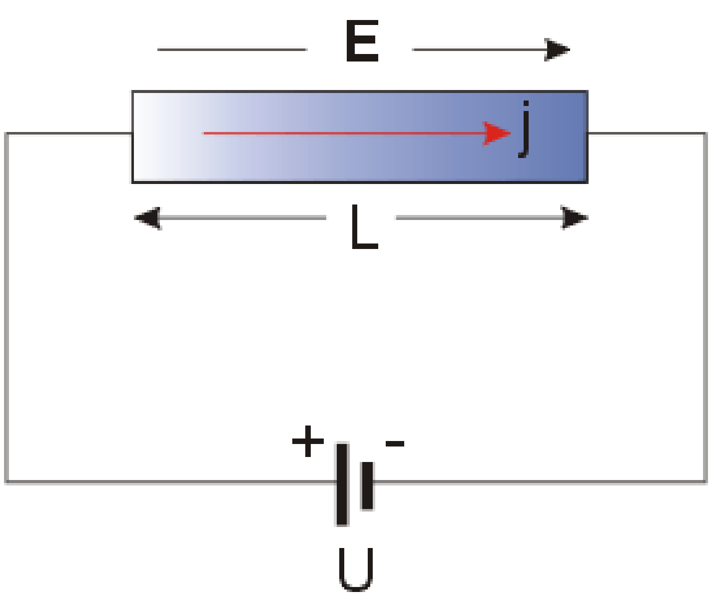
Wiedemann-Franz Law



$$\frac{\kappa}{\sigma} = LT$$

$\kappa =$ *thermal conductivity*

$\kappa = \quad {}_{e} + N_{L}$

$\kappa_{e} =$ *electron conductivity*

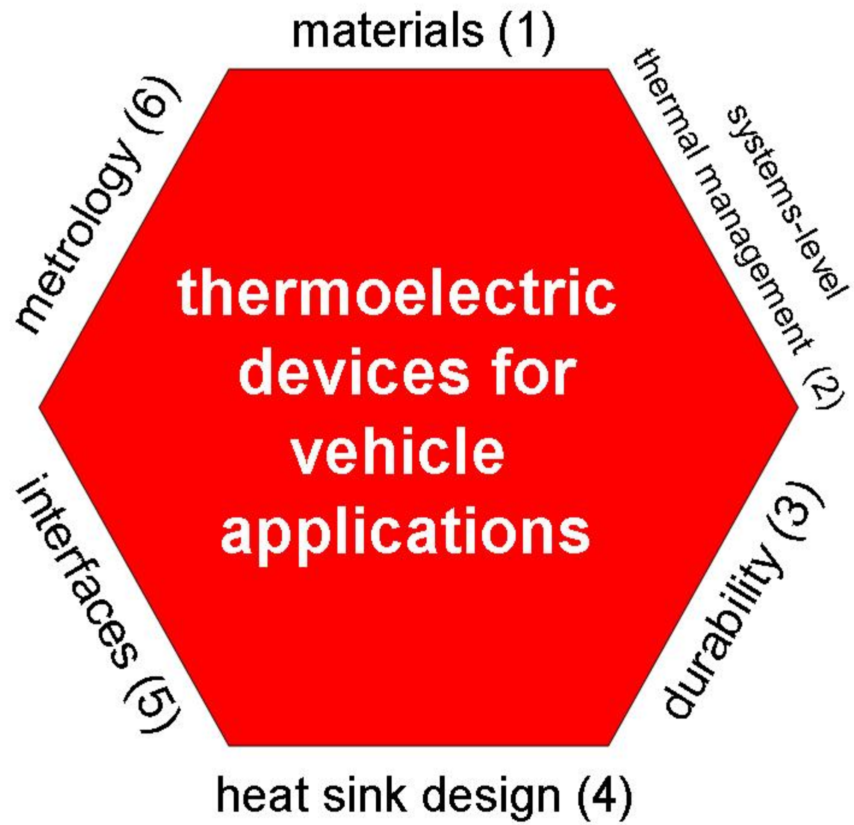
$\kappa_{L} =$ *lattice conductivity*

$\sigma =$ *electrical conductivity*

$L =$ *Lorentz number*

$T =$ *Absolute temperature*

Areas Targeted



Funding: $9M over three years ($4.5M from DOE; $4.5M from NSF)

Funded projects (2010)

Virginia Tech: An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicle. *Scott T Huxtable*

Stanford: Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces. *Kenneth E Goodson*

UT-Austin: High-Performance Thermoelectric Devices Based on Abundant Silicide Materials for Waste Heat Recovery. *Li Shi*

Texas A&M U.: Inorganic-Organic Hybrid Thermoelectrics. *Sreeram Vaddiraju*

UCLA: Integration of Advanced Materials, Interfaces, and Heat Transfer Augmentation Methods for Affordable and Durable Devices. *Yongho Ju*

UC-Santa Cruz: High Performance Thermoelectric Waste Heat Recovery System Based on Zintl Phase Materials with Embedded Nanoparticles. *Ali Shakouri*

Ohio State: Project SEEBECK-Shaving Energy Effectively by Engaging in Collaborative research and sharing Knowledge. *Joseph Heremans*

Purdue: Thermoelectrics for Automotive Waste Heat Recovery. *Xianfan Xu*

SUNY-Stony Brook: Integrated Design and Manufacturing of Cost Effective and Industrial-Scalable TEG for Vehicle Applications. *Lei Zuo*

Title of project: **Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces**

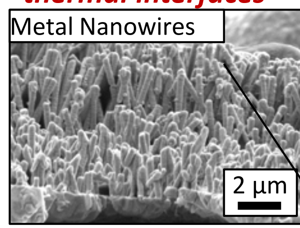
Academic PIs: **K.E. Goodson (Stanford University), G. Nolas (University of South Florida)**

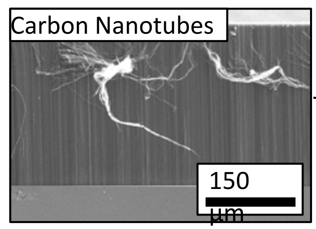
Industrial Collaborator: **B. Kozinsky (Robert Bosch LLC)**

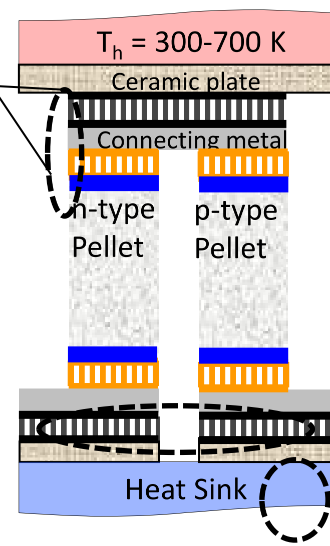
- **thermal interface materials** **carbon nanotube and metal nanowire arrays**
- **skutterudites and half-Heusler alloys**

Concepts developed to be used by Robert Bosch LLC.

Nanostructured thermal interfaces

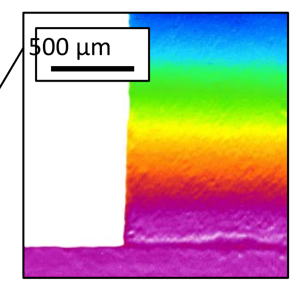






High-temperature skutterudite (Ba,Yb,Co,Sb Re structures)

High-temperature Infrared microscopy

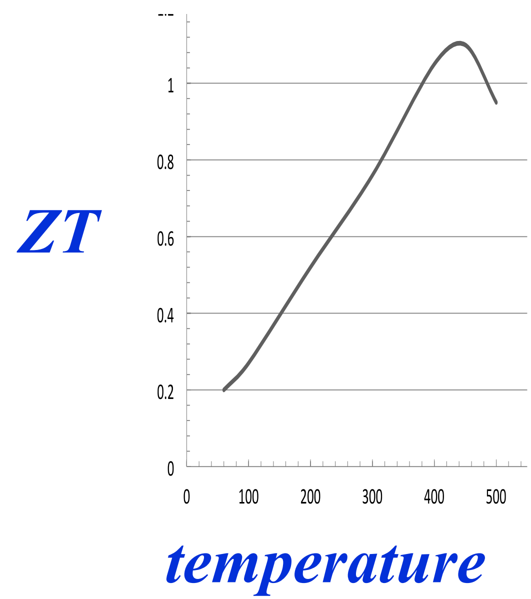


Title of project: **An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicles**

Academic PIs: **Scott T. Huxtable, Srinath V. Ekkad, and Shashank Priya, Virginia Tech**

Industrial Collaborator: **Andrew Miner, Romny Scientific, San Bruno, CA**

Developed *n-type MgSi based alloy (ZT ~1.1 @ 450C)* with a new mechanical alloying process that *is rapid, repeatable, and scalable to high volume production*



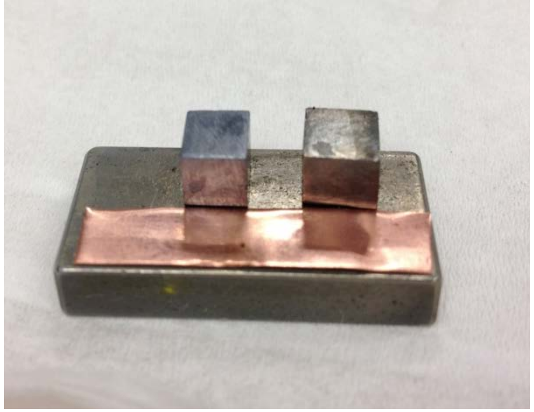
Two Tier 1 automotive suppliers to use these materials for TEGs

Title of project: **High-Performance Thermoelectric Devices Based on Abundant Silicide Materials for Vehicle Waste Heat Recovery**

Academic PIs: **Li Shi, John B. Goodenough, Matt J. Hall, Jianshi Zhou (U. of Texas at Austin); Song Jin (U. of Wisconsin-Madison)**

scalable method of synthesizing Mg_2Si-Mg_2Sn-Mg_2Ge ternary solid solutions with ZT ~ 1.08 at 800 K for Sb-doped $Mg_2Si_{0.4}Sn_{0.4}Ge_{0.2}$

system level finite different model for a thermoelectric heat exchanger.



A TEG module made of Mg_2Si based material as a n-type leg (left) and HMS based material as a p-type leg (right).

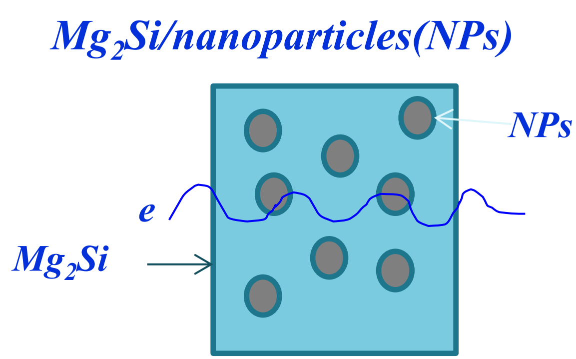
Title of project: **High performance TE system based on Zintl phase materials with embedded nanoparticles**

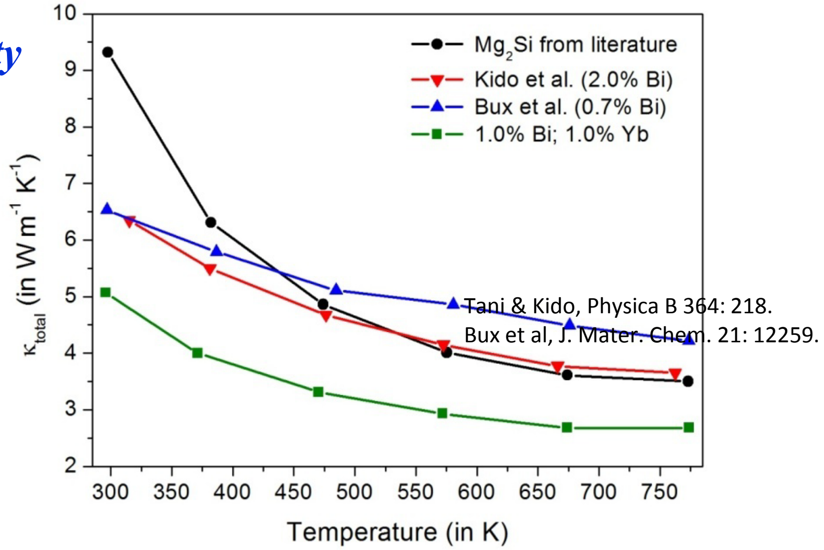
Academic PIs: A**. Shakouri (Purdue); Z. Bian (UC Santa Cruz); S. M. Kauzlarich (UC Davis)**
Industrial partners: **NASA JPL**

scalable* synthetic method to produce *Mg_2Si nanocomposites - ZT ~ 0.7 at 500˚C - by reducing thermal conductivity.

JPL/NASA collaborations/characterization

Thermal conductivity



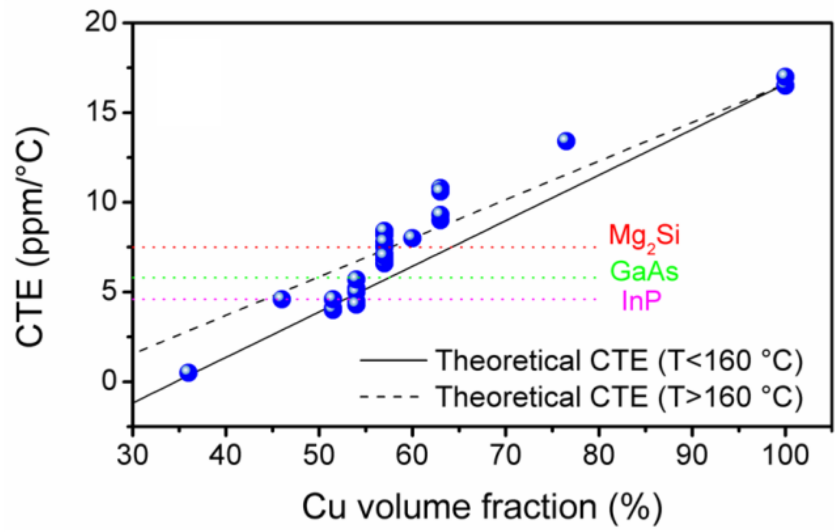


Title of project: **Integration of Advanced Materials and Interfaces for Durable Thermoelectric Automobile Exhaust Waste Heat Harvesting Devices**

Academic PIs: **Y. Sungtaek Ju and Bruce Dunn (UCLA)**

Industrial Collaborators: **JPL**

***metal matrix nano-composites with tailorable CTEs for electrodes and contact materials* in TEG modules.**



Technology developed will be used by thermoelectric module manufacturers

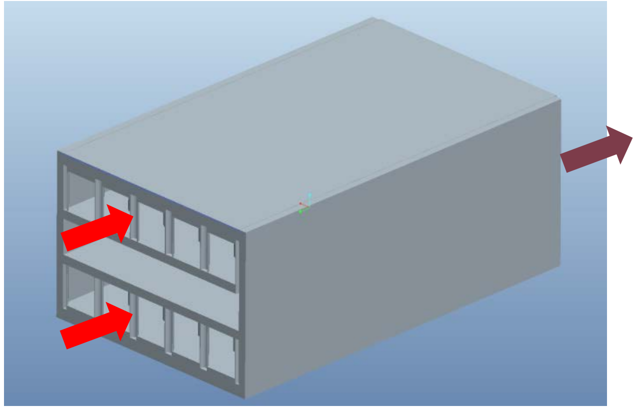
Title of project: **Purdue – GM Partnership on Thermoelectrics for Automotive Waste Heat Recovery**

Academic PIs: **Xianfan Xu, Timothy S. Fisher, Steven D. Heister, Yue Wu, Timothy D. Sands, Purdue University**

Industrial Collaborators: **Gregory Meisner, James Salvador, General Motors R&D**

novel hot side (proprietary) heat exchanger with high heat transfer coefficient and low pressure loss

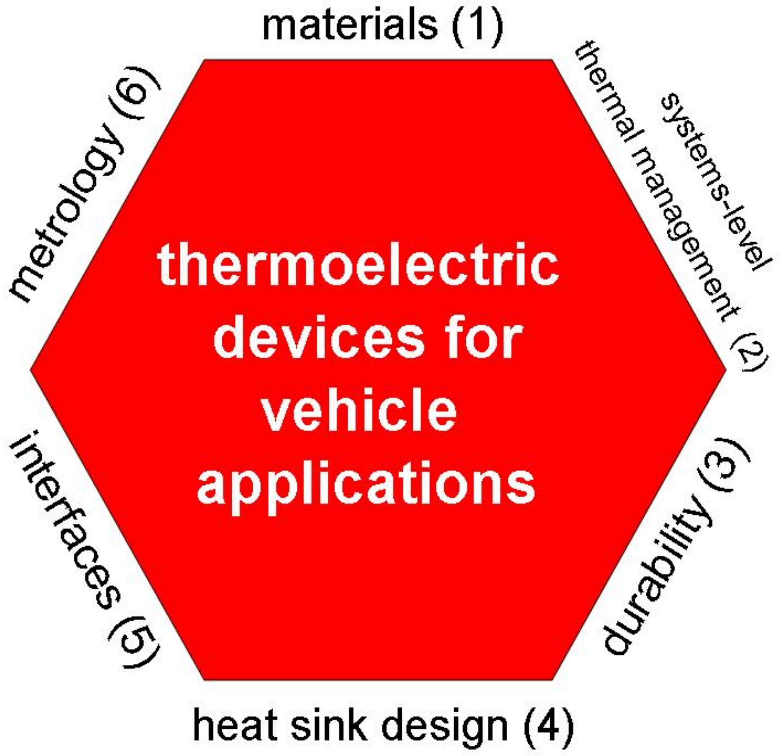
GM to implement design



Hot side heat exchanger (conceptual drawing; details removed)

The Way Forward

- Large volume/commercially viable production
- Improve thermoelectric materials and TEG efficiency
- Prototype evaluation in vehicles



THERMOELECTRICS: THE NEW GREEN AUTOMOTIVE TECHNOLOGY