THERMOELECTRIC DEVELOPMENTS FOR VEHICULAR APPLICATIONS

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Washington, D.C.

Diesel Engine-Efficiency and Emissions Research (DEER) Conference
Detroit, MI
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View from the Flying Bridge

VIEW FROM THE FLYING BRIDGE

- **One Level Above the Bridge**
  - **Enhanced View of the Horizon**
  - **See "Perhapsatron" Mirage or an Widely Encompassing Range of High Efficiency Thermoelectric Energy Saving Applications?**
- **Here is the Presentation……You be the Judge**

OVERVIEW

❑Thermoelectric Applications - Now to Near Term

- Historical
- Analytical
- Seebeck Effect Thermoelectric Generators
- Peltier Effect Thermoelectric Cooling/Heating

- DOE/NETL Vehicular Thermoelectric Generators
  - 2 Teams SI Gasoline Engine Powertrains
  - 2 Teams Heavy Duty Truck Diesel Engines

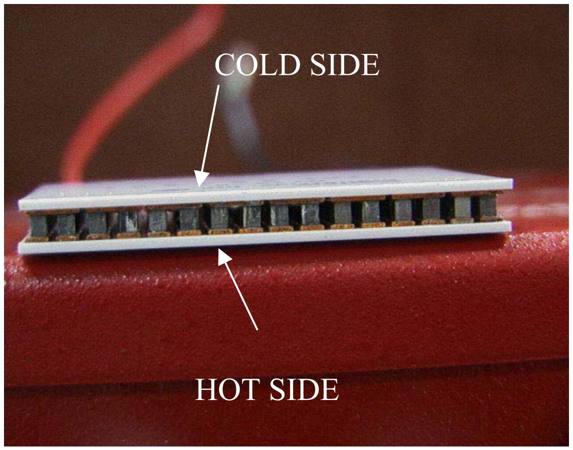
Emerging High Efficiency Thermoelectrics

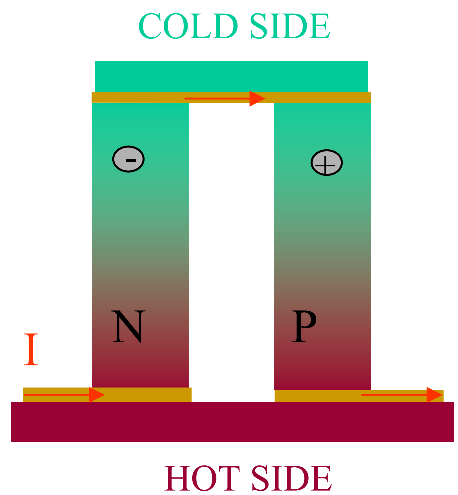
Recent Quantum Well Results at Hi-Z Technologies

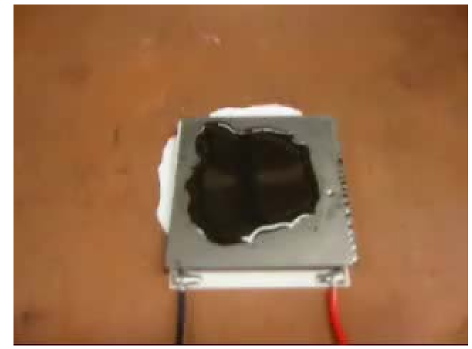
Potential Scale up Nanoscale Thermoelectrics

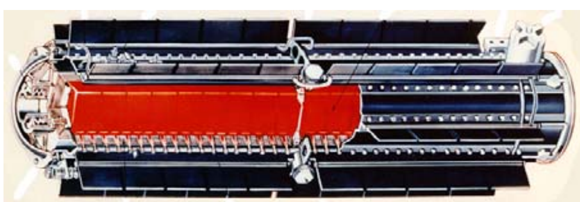
High Rate Sputtering Equipment and scale-up challenges

THERMOELECTRIC DEVICES









GPHS Radioisotope Thermoelectric Generator

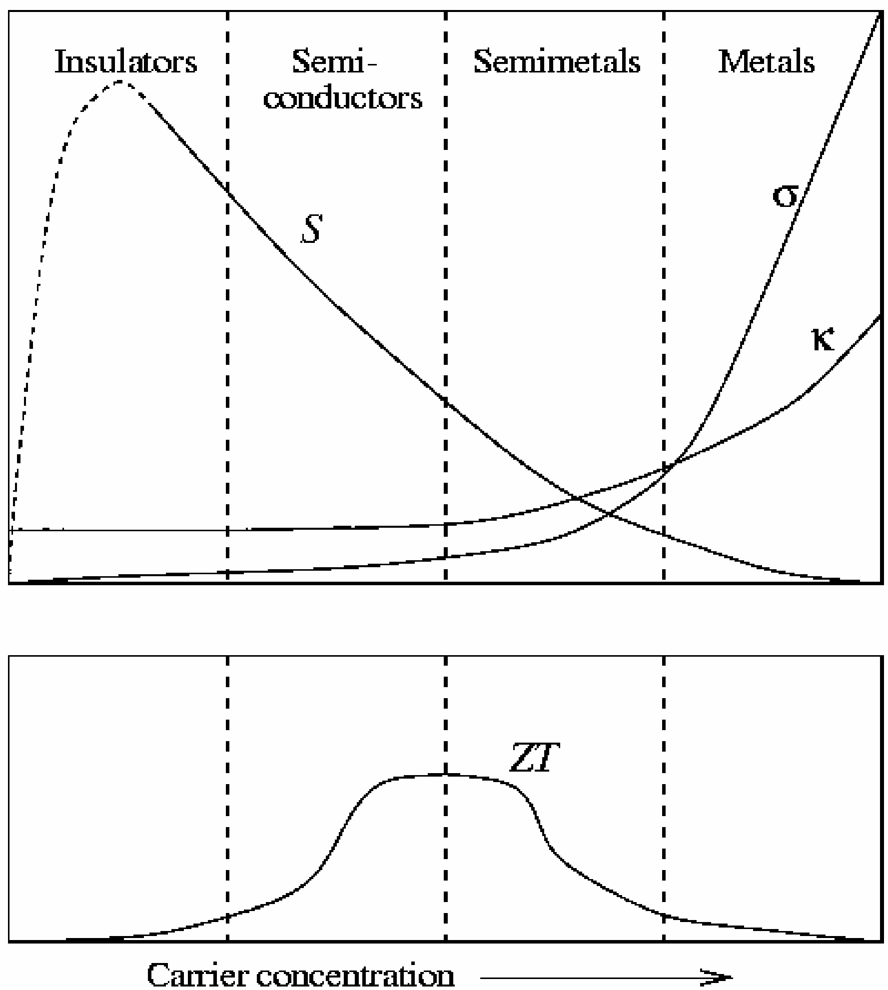
Nondimensional Figure of Merit

Joule Heating → σ; **Seebeck Coeff. Electron Cooling** → S^2

$$ZT = \frac{\sigma S^2 T}{k}$$

Reverse Heat Leakage Through Heat Conduction → k

Thermoelectric Properties of Conventional Materials



To increase Z, we want

$$S\uparrow, \quad \sigma\uparrow, \quad \kappa\downarrow$$

but

$$S\uparrow \Leftrightarrow \sigma\downarrow$$
$$\sigma\uparrow \Leftrightarrow \kappa\uparrow$$

With known conventional solids, a limit to Z is rapidly obtained.

Best alloy: $Bi_{0.5}Sb_{1.5}Te_3$

$ZT \sim 1$ @ 300 K

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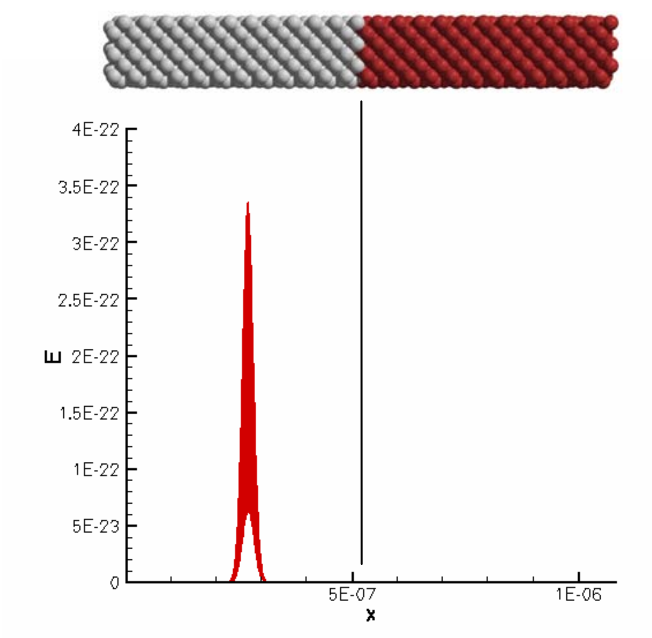
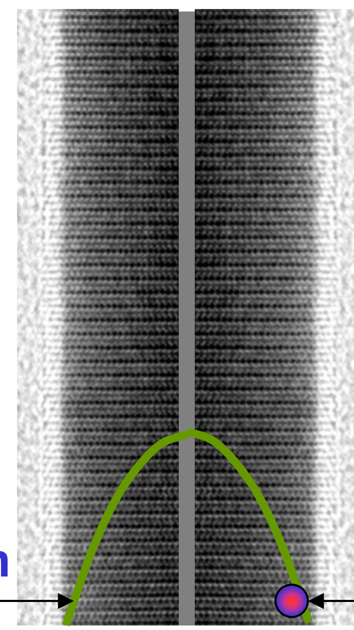
Nanoscale Effects for Thermoelectrics

Interfaces that Scatter Phonons but not Electrons

	Electrons	Phonons
Mean Free Path	Λ=10-100 nm	Λ=10-100 nm
Wavelength	λ=10-50 nm	λ=1 nm





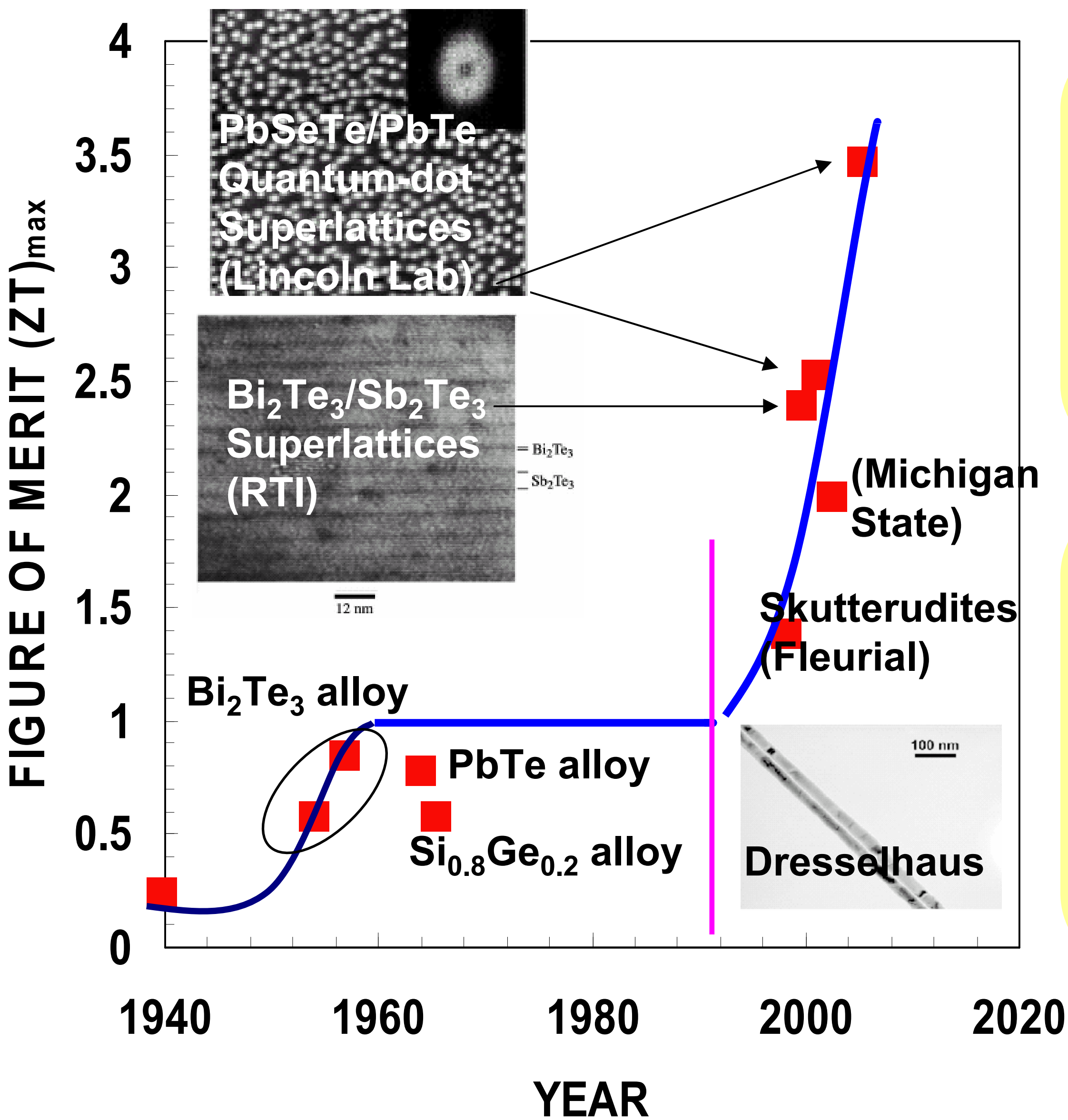
Definition of PHONON

- **Phonon in solid-state physics is a quantum of lattice vibrational energy. In analogy to a phonon (a quantum of light), a phonon is viewed as a wave packet with particle like properties**

- **The way phonons behave determines or affects various properties of solids.**

- **Thermal conductivity, for instance, is explained by phonon interactions.**

State-of-the-Art in Thermoelectrics



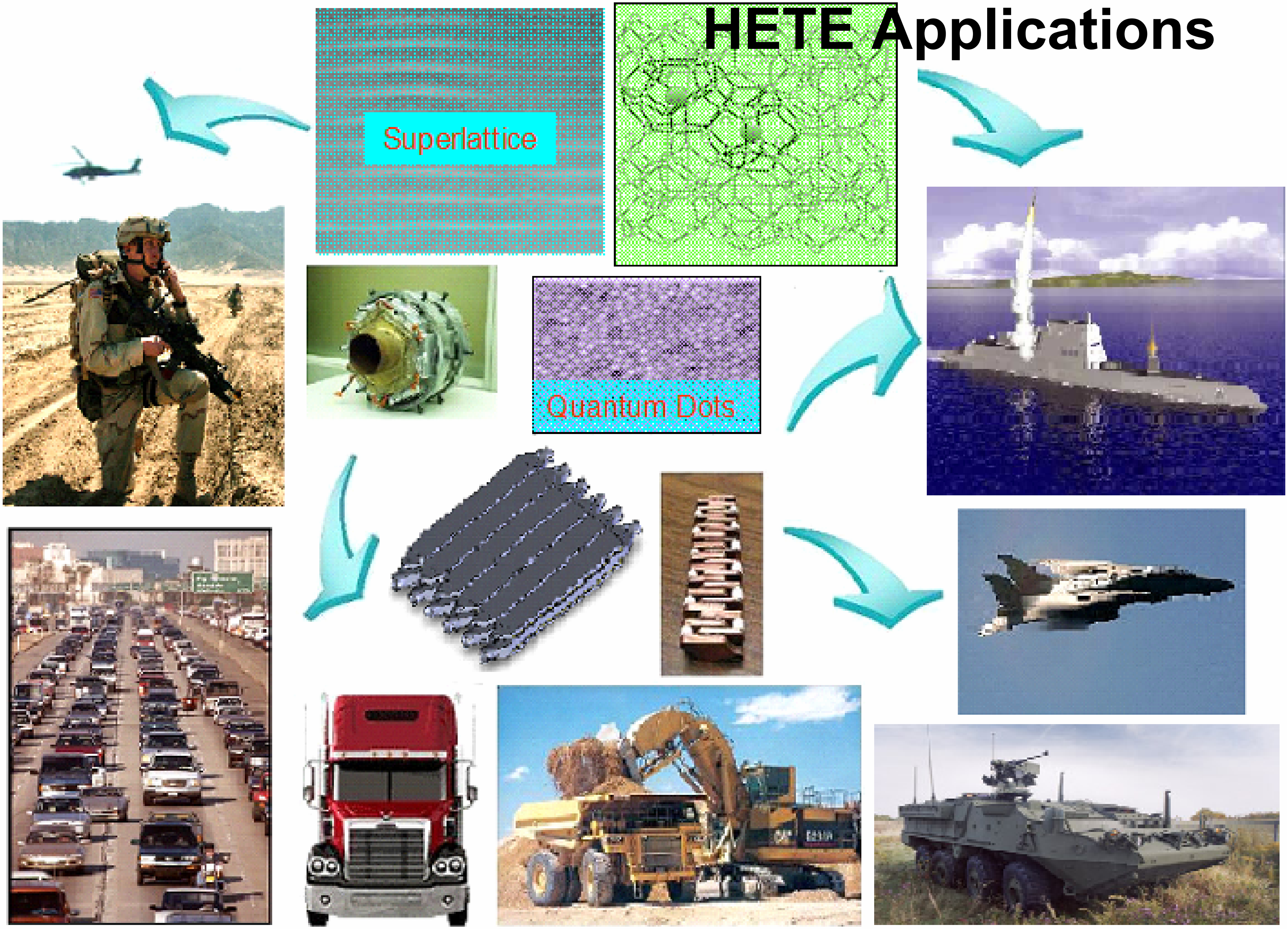
PbTe/PbSeTe	Nano	Bulk
$S^2\sigma$ (μW/cmK^2)	32	28
k (W/mK)	0.6	2.5
ZT (T=300K)	1.6	0.3

Harman et al., Science, 2003

Bi_2Te_3/Sb_2Te_3	Nano	Bulk
$S^2\sigma$ (μW/cmK^2)	40	50.9
k (W/mK)	0.6	1.45
ZT (T=300K)	2.4	1.0

Venkatasubramanian et al., Nature, 2002.

HETE Applications



Thermoelectric Wristwatch

CITIZEN Eco-Drive Thermo Watch

> Converts temperature difference between body and surrounding air into electrical energy

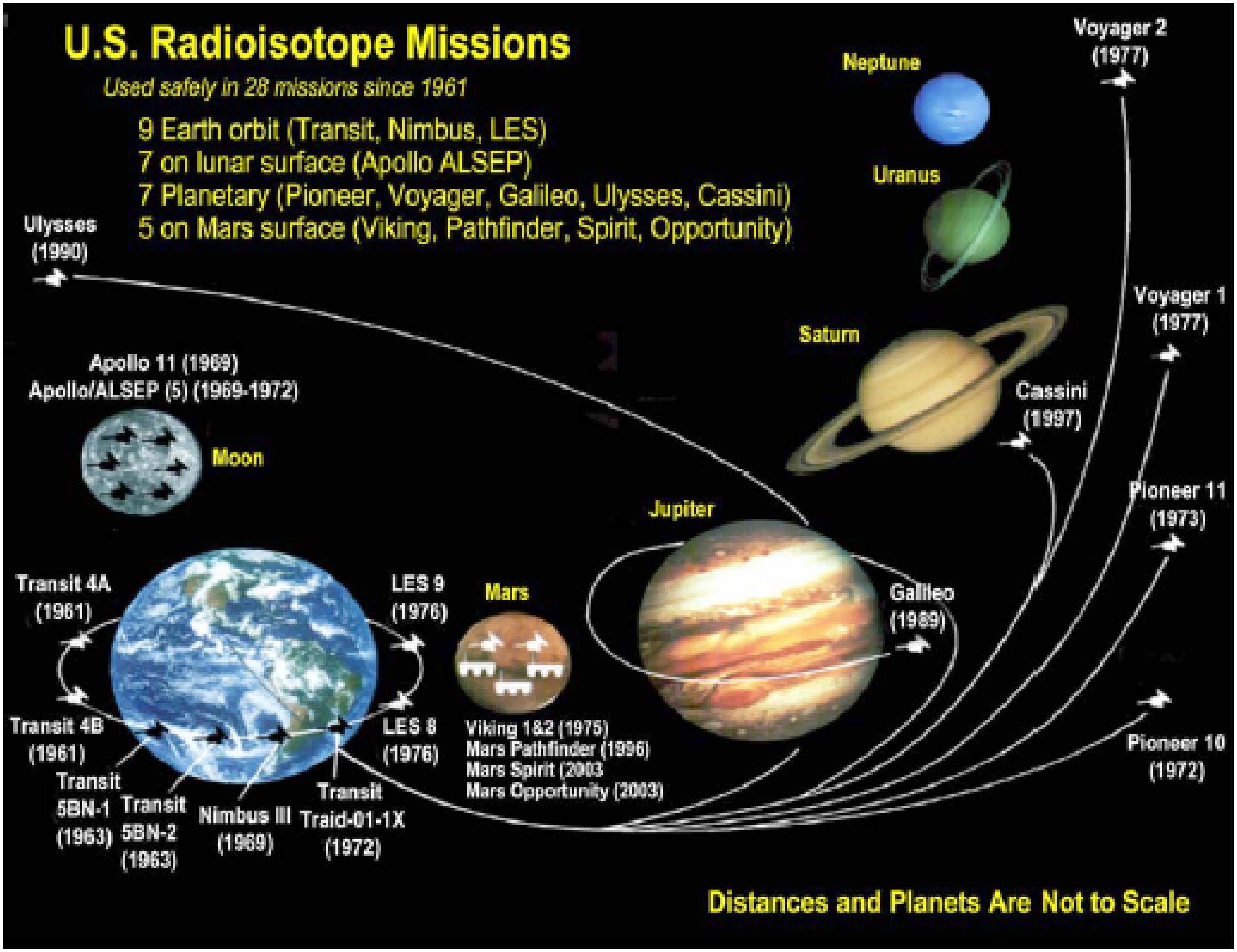
> No battery change needed

> When not being worn, second hand moves in 10-second increments (non power generation mode)

> Number of semiconductors in thermocouple array: 1,242 pairs

> Operating time from a full charge: Approx. 6 months (approx. 16 months in power saving mode)

Spacecraft using Radioisotope Thermoelectric Generators

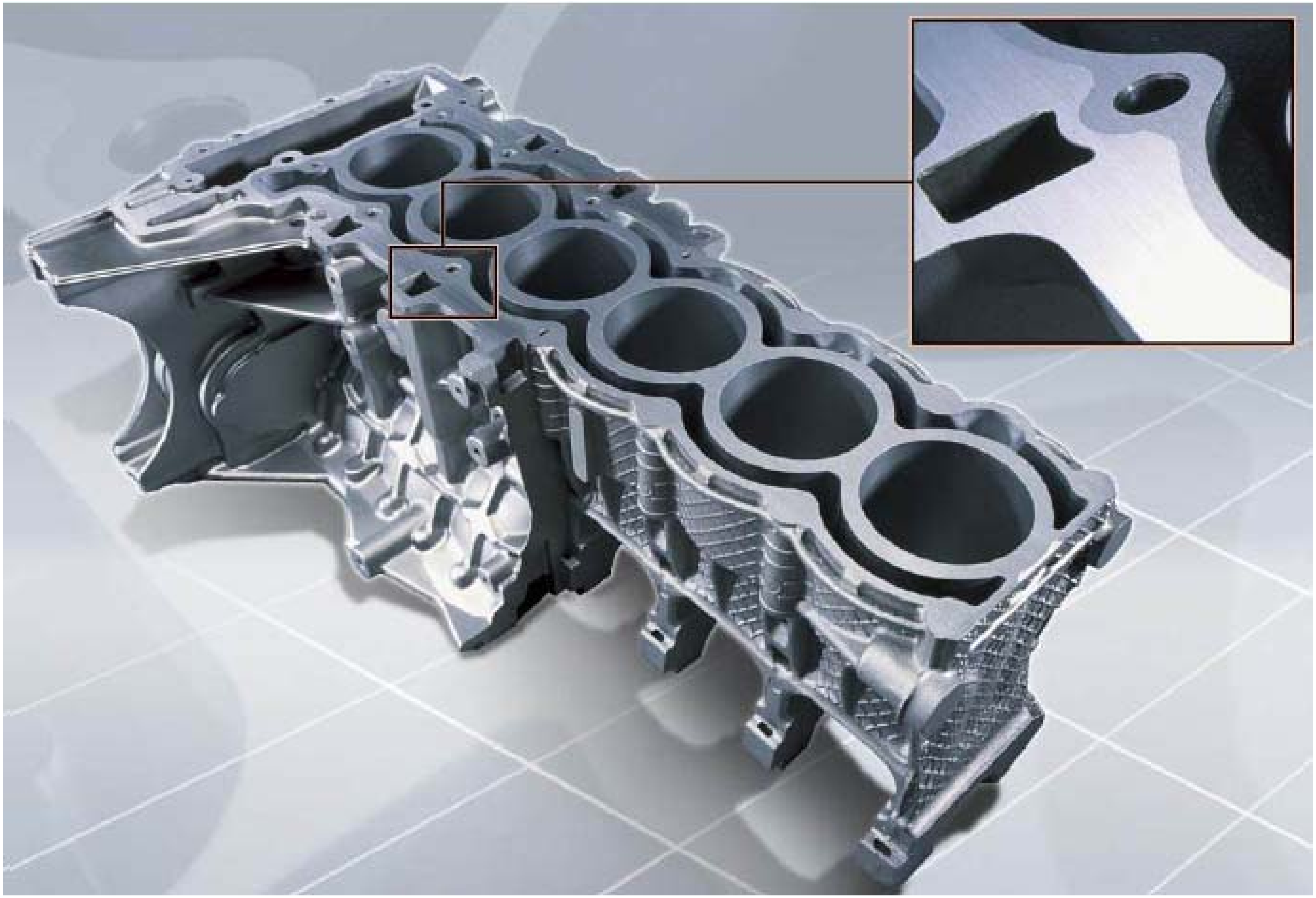


TE Energy Recovery Benefit

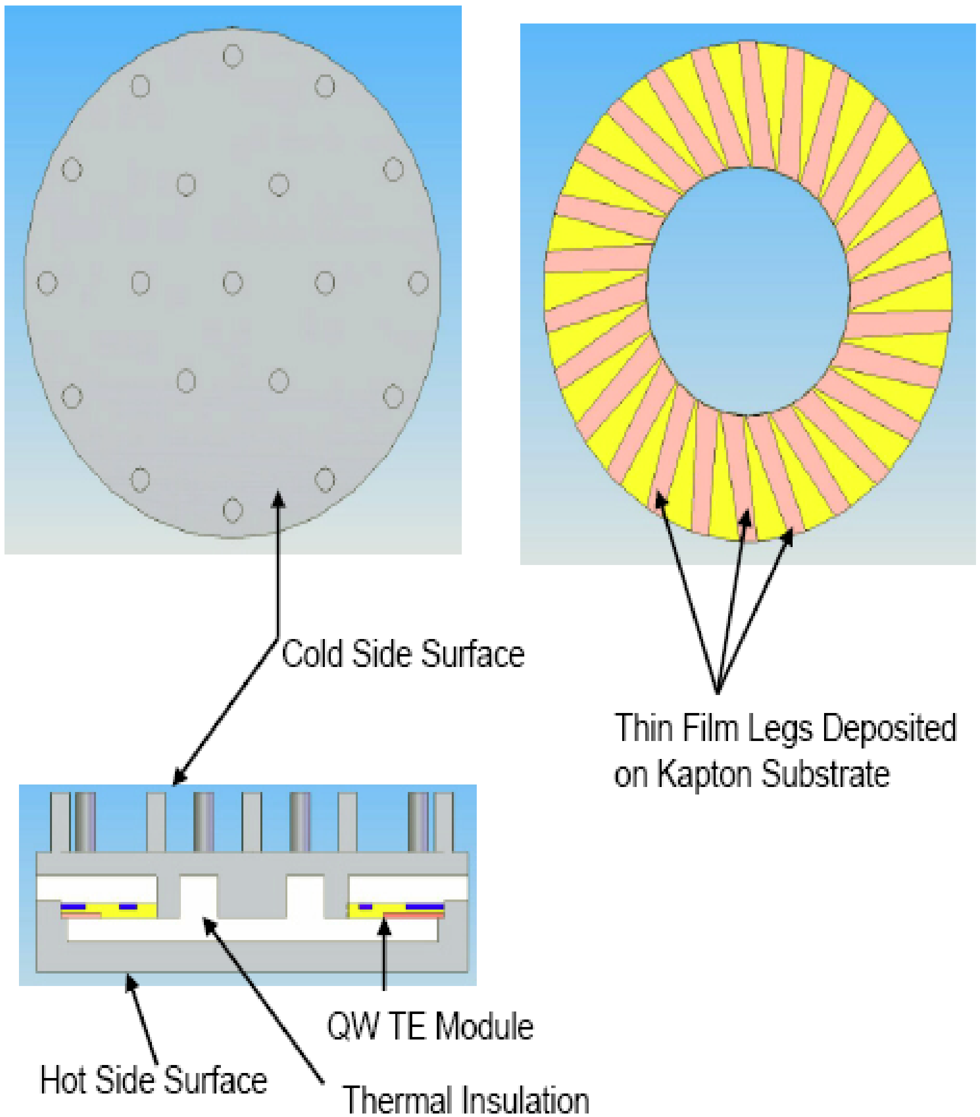
2004 Jaguar XJ

- Use of aluminum results in a 500 lb weight reduction, with consequent fuel saving
- Currently, only luxury cars use Aluminum frame and body, due to high cost.
- If we can recover sufficient energy from the Aluminum manufacture process, it may become feasible to use it for mass-produced cars, due to reduced cost.

BMW's Magnesium Engine Block



Power-Harvesting QWTE Power Supply for Navy Wireless Sensors



Small size (1 in^3) requirement satisfied using QW TEG

Provides power for wireless sensors:

- 5 mW at 3 V using 41°C ΔT from ship interior thermal environment

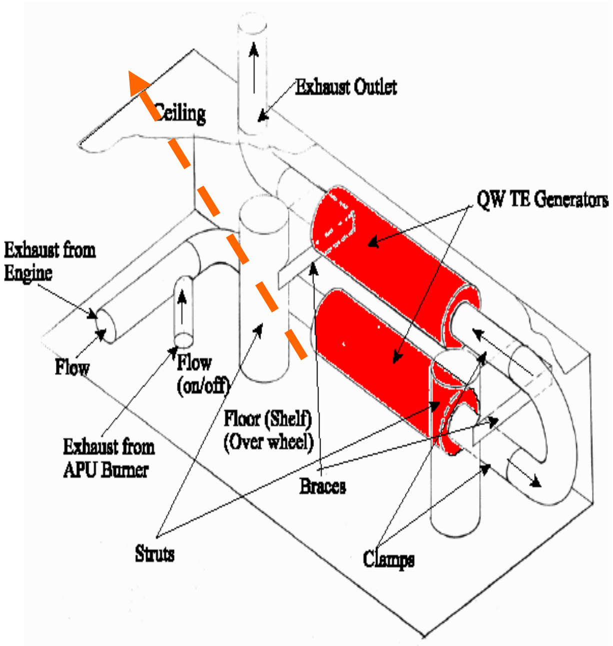
Generator dimensions:

- 1 in^2 footprint
- ½ inch height

Stryker Vehicle Under Armor Quantum Well Thermoelectric Generators

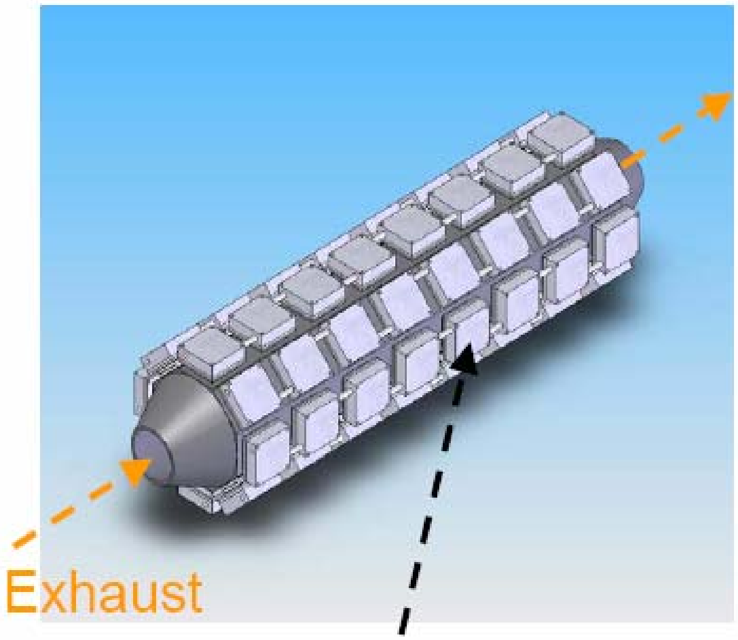
15% Efficiency Predicted with two 5 kW_e QW TE Generators Driven by Vehicle Exhaust

When Parked APU Burner to Provide Power Using Same Thermoelectric Generator



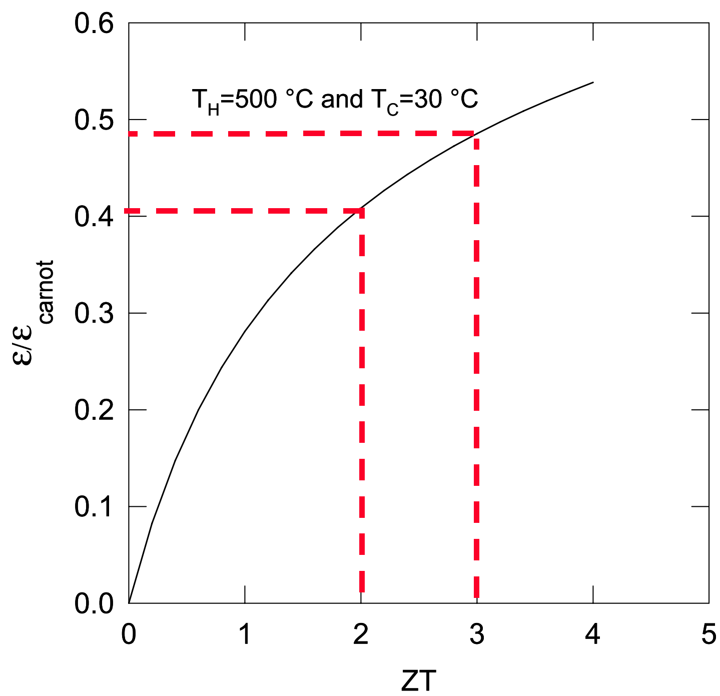
Five kW_e Quantum Well Thermoelectric Generator

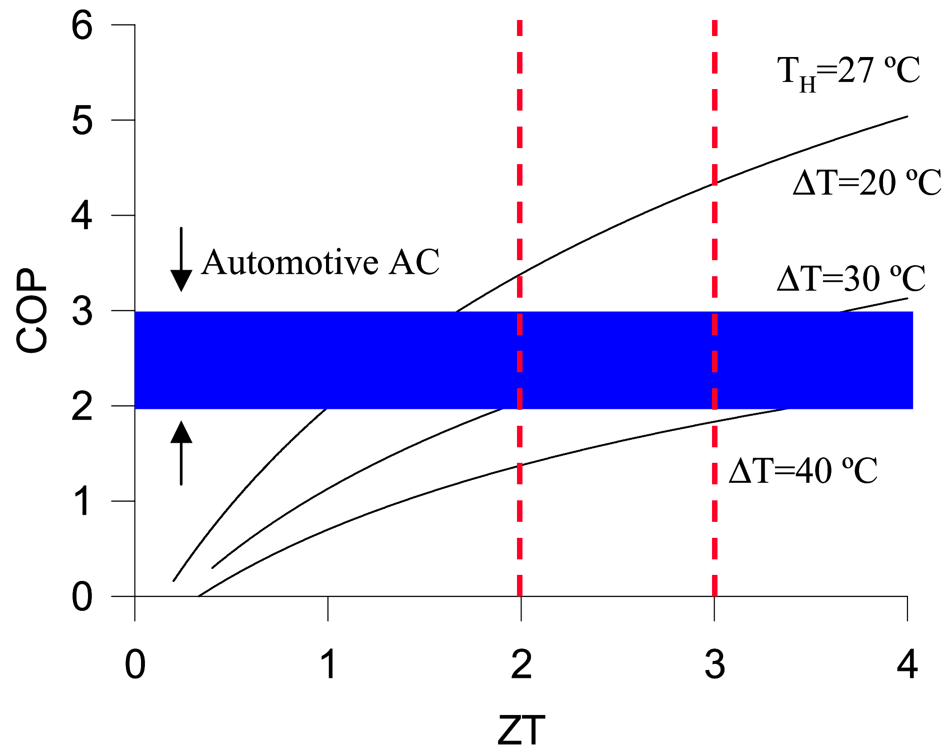
- Contains 64 QW Modules in Octagonal Arrangement
- Integrated Coolant & QW Module Unit
  - Each QW Module in Compression
- QW Generator provides 5x power of current Bi_2Te_3 module in same space
  - Fits in 27 inch length and 10 inch diameter with cover plate



QW TE Modules & Coolant Heat Exchangers

TE Power Generation & Refrigeration





ZT ~ 2 to 3 would warrant TE technology development for large scale applications

Thermoelectric Applications at United Technologies

today…

…tomorrow

Today:

POWER SOURCE

- Batteries

CLIMATE CONTROL

- None

Tomorrow:

POWER SOURCE

- Logistic fuel based system

CLIMATE CONTROL

- Thermoelectric based cooling/heating
- On-demand

IMPACT

- >30% weight savings over existing systems

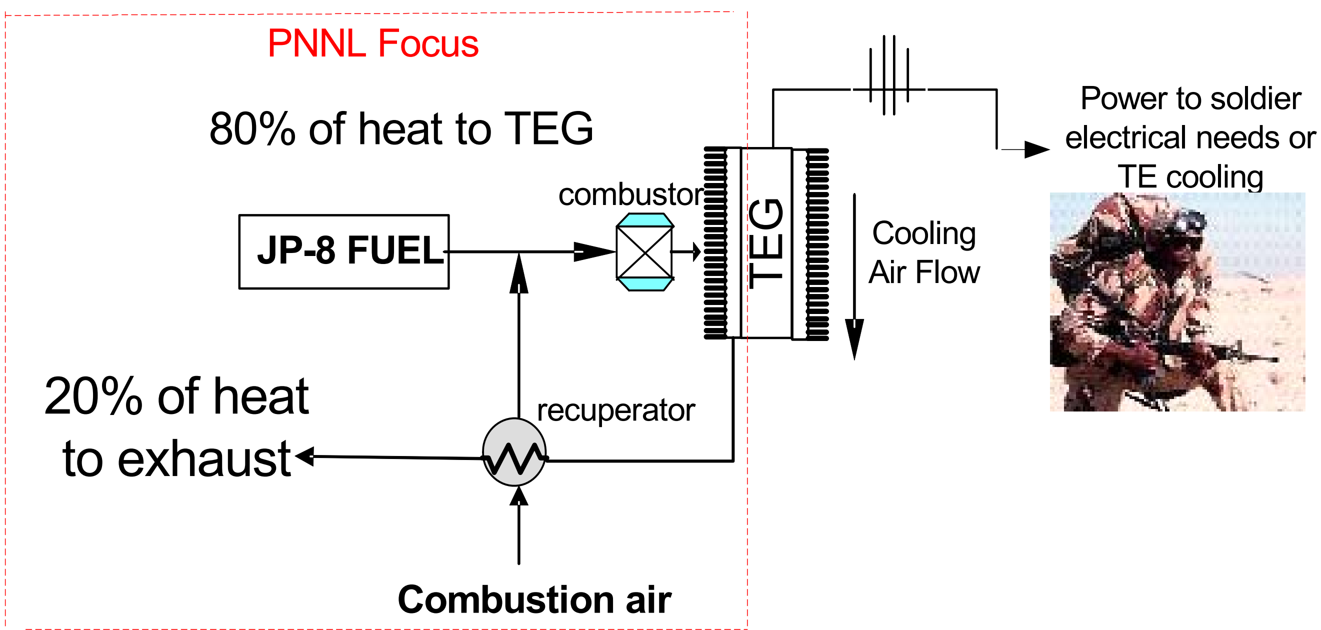
Assumptions
12 hour mission @ 110°F ambient temperature

Enabled by Thermoelectrics (TE)

DARPA TTO Program Manager: Ed van Reuth

Man-Portable Power (DARPA/UTRC Project)

- Heat-exchanger design optimization for 200 W_e TE-based lightweight power generator
- Developed mass-optimized designs for air recuperator and cold-side TEG heat sink
- Design total system mass at 3 kg



Global Climate Warming

R-134a refrigerant gas is the most common working fluid in vehicular air conditioners (A/C) since 11/15/95.

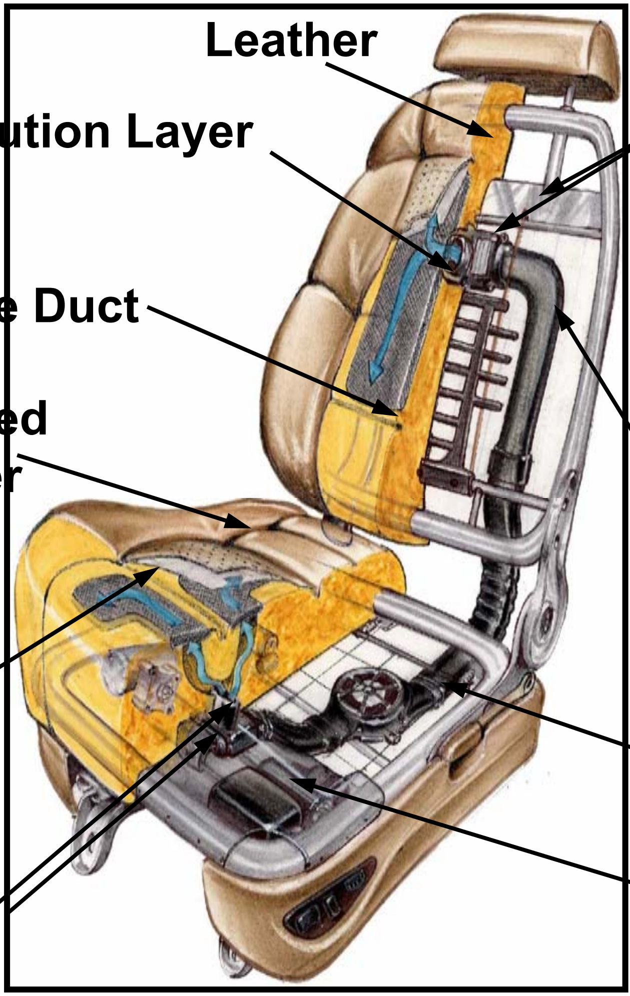
-Replaced Freon gas which was detrimental to Ozone layer

- R-134a has 1,300 times greater greenhouse gas impact than CO_2
- > Car air conditioners (A/C) leak 10 to 70 g/year

  > 90 % personal vehicles in North America & Asia and 87 % European cars have A/C
- Peltier thermoelectric HVAC systems significantly reduce
- Man's contribution to Greenhouse Gases
- While improving fuel economy

Climate Control Seat™ (CCS) System Vehicle Application

Production CCS Assembly



National Impacts of Automotive A/C

- 7-8 Billion Gallons/Yr of Fuel Use for Automotive A/C (NREL)
- ~6% of our National Light-Duty Fuel Use
- Centralized Automotive A/C Systems Require ~ 4-5kW of Power Use
- Smaller De-Centralized A/C Systems Could Require ~2-3 kW of Power
  - ZT> 2.0 Competitive with Refrigerant Gas Systems

Automotive Thermoelectric Air Conditioning

- ZT ~ 1; COP ~ 0.9-1.0; Distributed HVAC System; P ~ 2 kW; Power Off Alternator
  - Decrease ~ 0.8 mpg/vehicle (0.8/27.5 ~ 0.029)
  - Increase ~ 1.9 Billion Gallons of Gasoline/Year Because of Low Alternator Efficiency
- ZT ~ 2; COP ~ 2; Distributed HVAC System; P ~ 1 KW; Power Off Alternator
  - Increase ~ 1.1 mpg/vehicle (1.1/27.5 ~ 0.04)
  - Save 2.6 Billion Gallons of Gasoline/ Yr
- Either ZT Case; Power From Thermoelectric Generator Converting Engine Exhaust Heat to Electricity
  - Increase ~ 3 mpg/vehicle (3/27.5 ~ 0.11)
  - Save ~ 7.1 Billion Gallons of Gasoline / Year

(Assumes: 3 kW for AC, 3 kW = 3 mpg, 130 M Gallons / Yr for Passenger Cars)

Hendricks - PNNL

Thermoelectrics Replacing Gas Compressor Refrigeration ?

TODAY

Thermoelectric
Hot & Cold Mini Fridge
(1.5 ft^3)

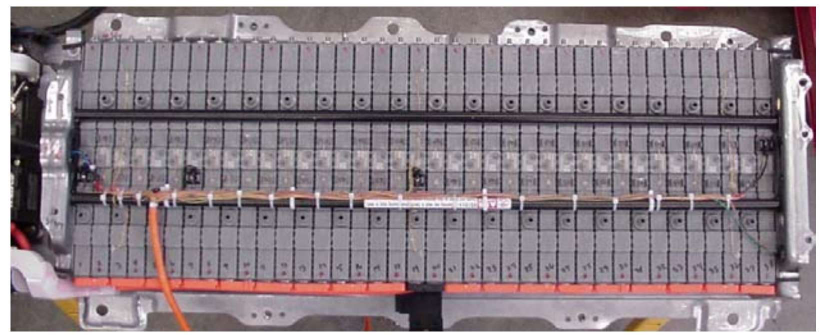
FUTURE ?

Side-by-side
Refrigerator/Freezer
(27.5 ft^3)

Battery Temperature Impacts HEV/EV

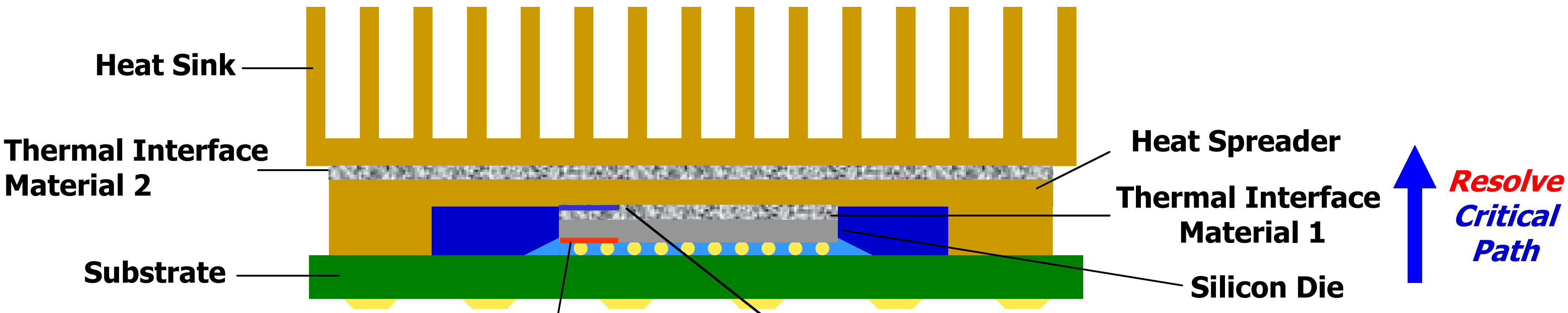
Temperature affects battery operation

- > Round trip efficiency and charge acceptance
- > Power and energy
- > Safety and reliability
- > Life and life cycle cost



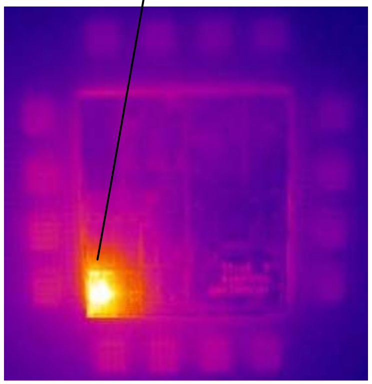
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost

Embedded Semiconductor Cooling Removes Heat From Die to Heat Sink

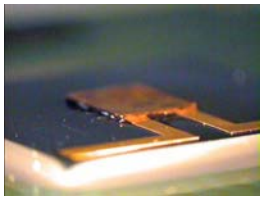


Hotspots effect

- ❑ Reliability
- ❑ Performance
- ❑ Package cost



Nextreme's solution



100 μm thickness

Embedded Thermoelectric in IC

- Active micro-cooling of hotspot
- Reduces total power cooled
- Simplifies package

Vehicle / Engine Selection

Selected vehicle platform (BMW 530i, MY2006)

Selected engine platform (Inline 6 cylinder, 3.0 l displacement)

- The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).

- The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe

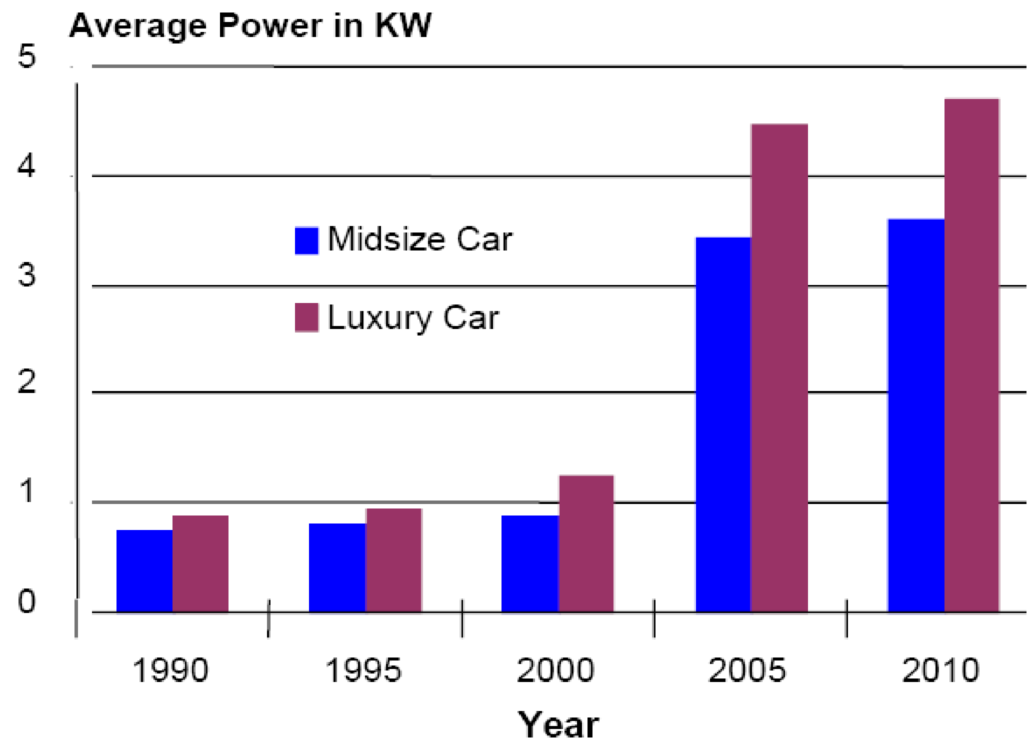
Waste Heat Utilization

- Where will Vehicular Thermoelectric Generator Electricity Directly Converted from Engine Waste Heat be Used?

Increasing Electrical Power Requirements for Vehicles

- Increased electrical power needs are being driven by advanced IC Engines for enhanced performance, emission controls, and creature comforts

  - **Stability controls**
  - **Telematics**
  - **Collision avoidance systems**
  - **Onstar Communication systems**
  - **Navigation systems**
  - **Steer by-wire**
  - **Electronic braking**
  - **Powertrain/body controllers & Sensors**



- These requirements are beyond the capabilities of the current generators and require supplemental electrical generation, such as from a TE waste heat recovery unit
- Juhui Yang GM

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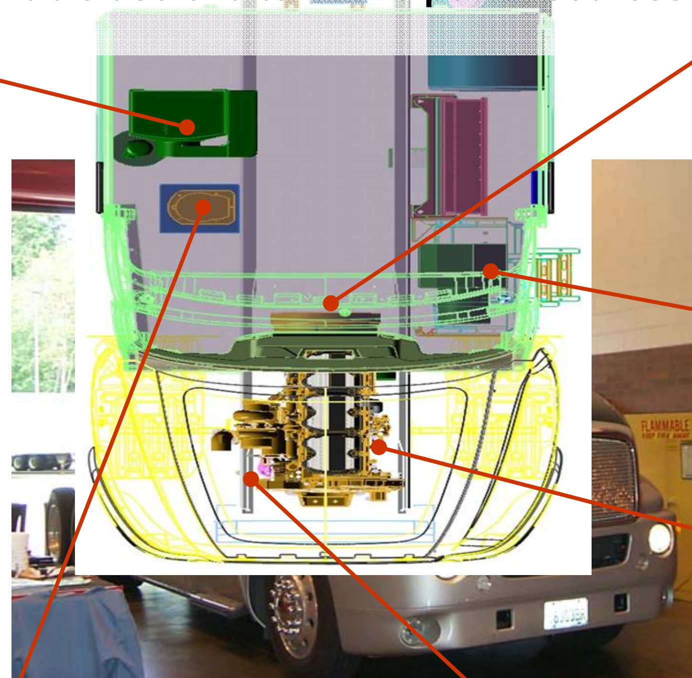
Beltless or More Electric Engine

Truck Electrification

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

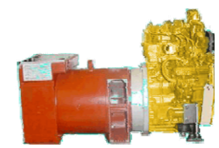
Modular HVAC

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



Auxiliary Power Unit

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

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

Down Converter

Supplies
12 V Battery from DC Bus

Compressed Air Module

Supplies compressed air for brakes and ride control

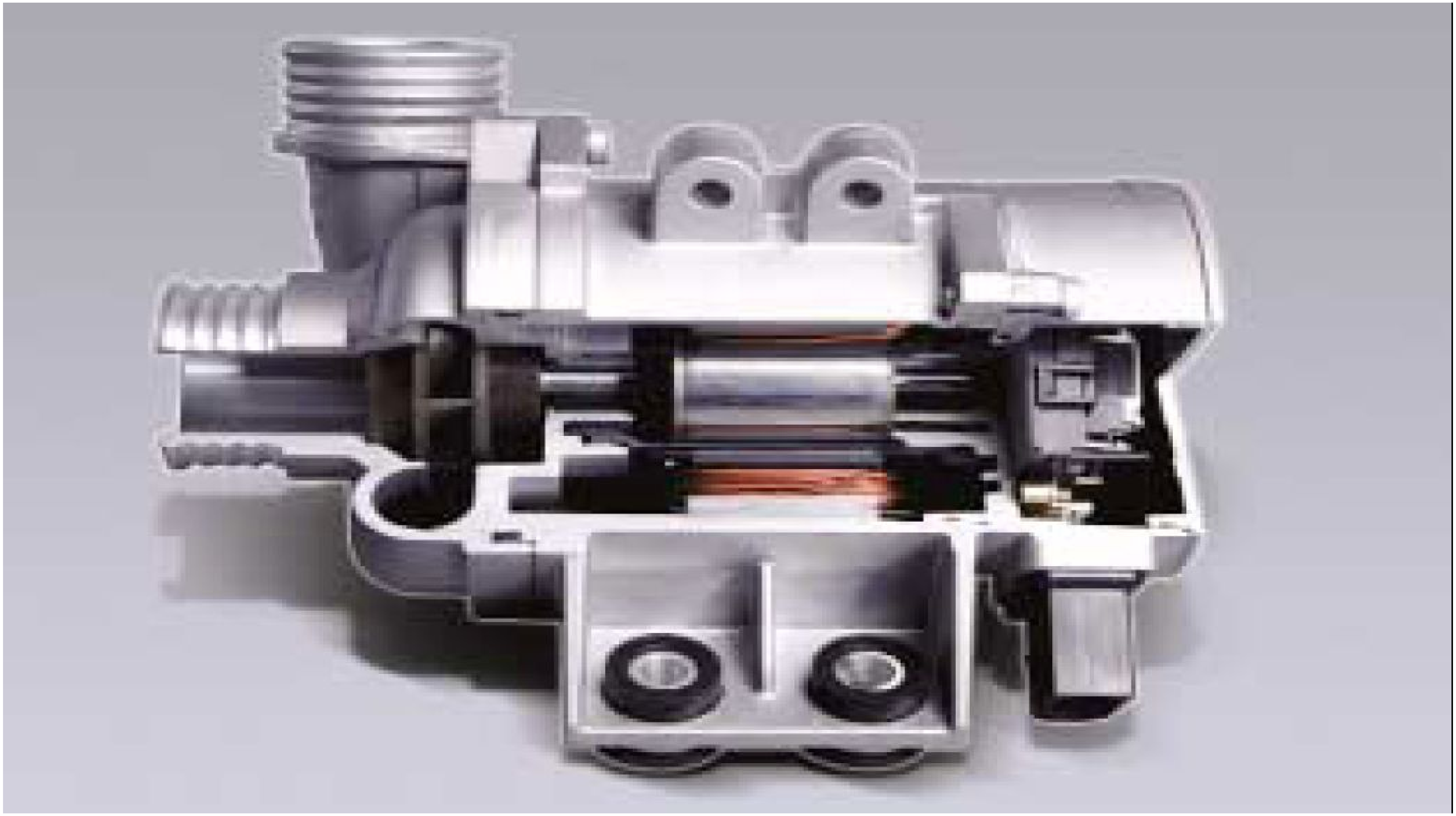
Electric Water Pump

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

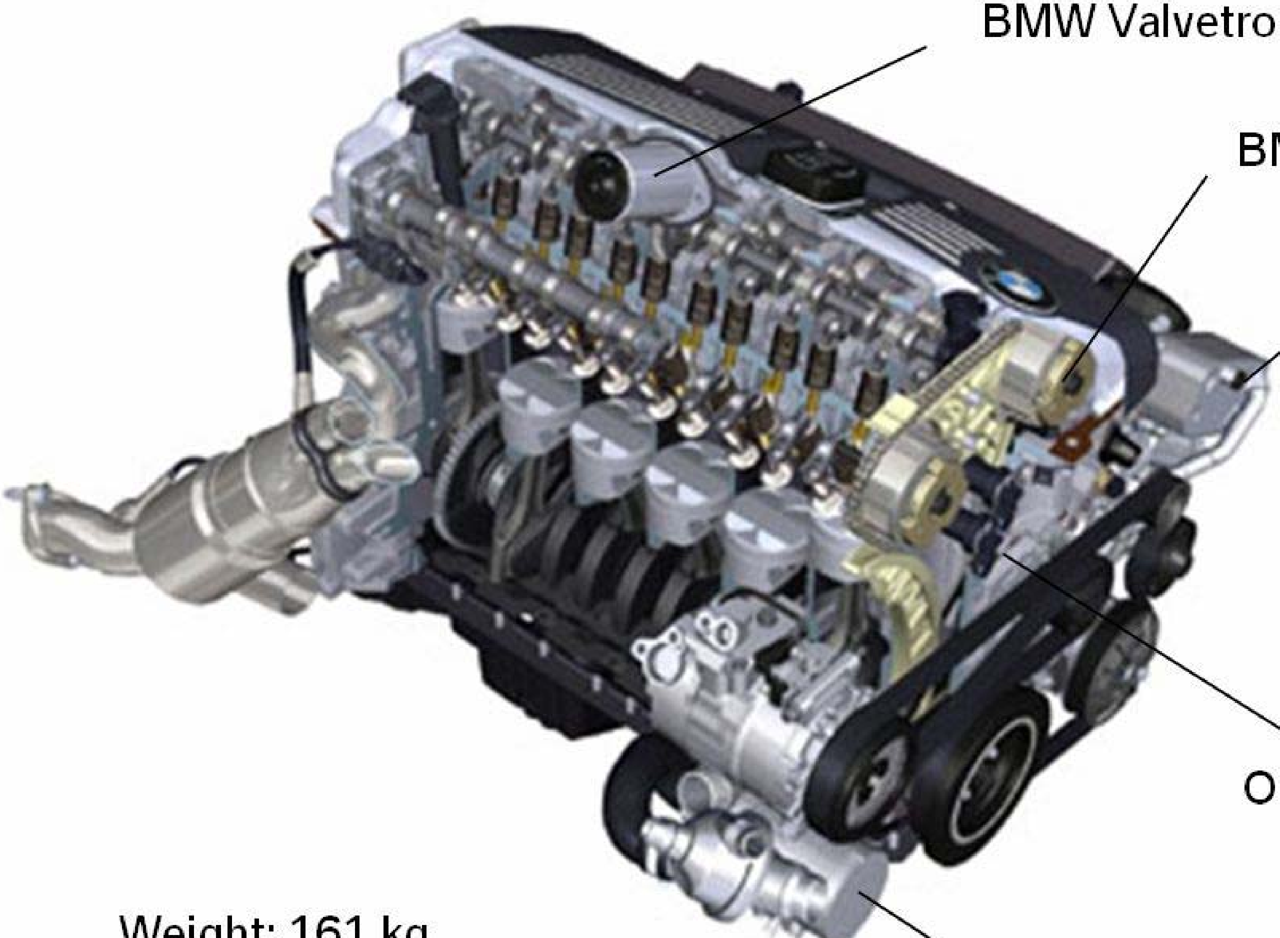
Electric Oil Pump

Variable speed
Higher efficiency

BMW's Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %

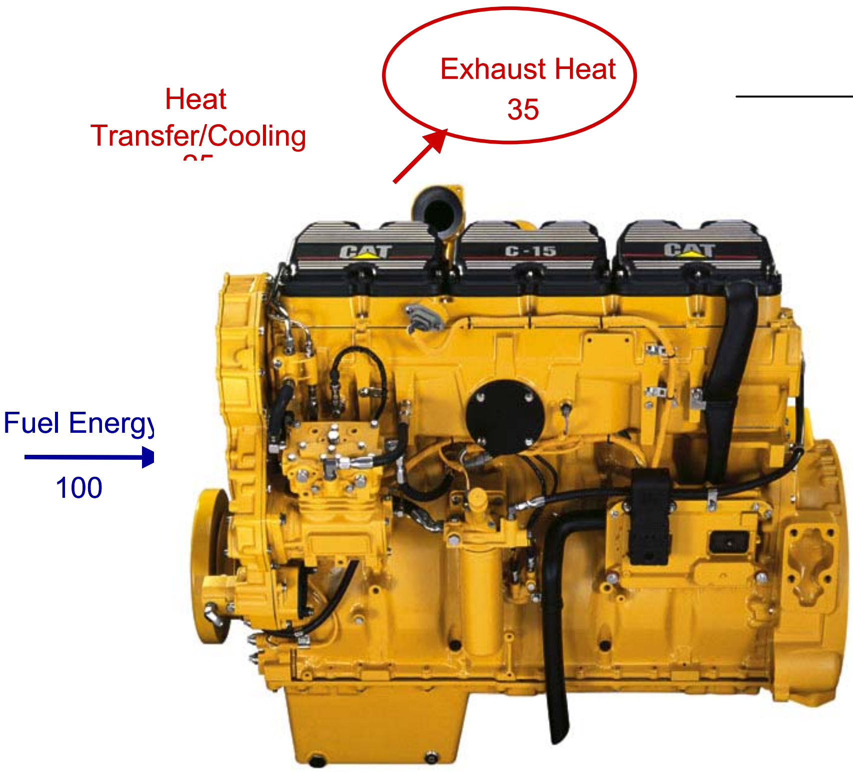


BMW Series 5 Engine with Electric Water pump

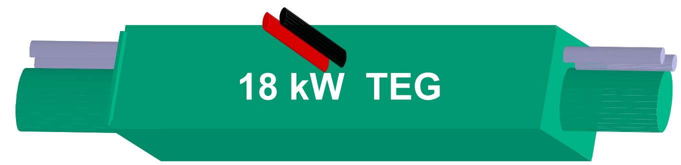


Weight: 161 kg
Power: 190 kW
Max engine speed: 7000 rpm

Thermoelectric Applications at UTRC
DOE Waste Heat Utilization Program



Caterpillar Class 8 Truck
Energy Audit of Engine



Project Objective: Improve fuel efficiency of a heavy-duty, on-highway truck by 10%

Phase I Results:

- 18 kW TE generator designed
- Full system projects 8 – 8.5% improvement in fuel economy
- critical customers demand, to buy, 2 – 9% improvement in fuel economy

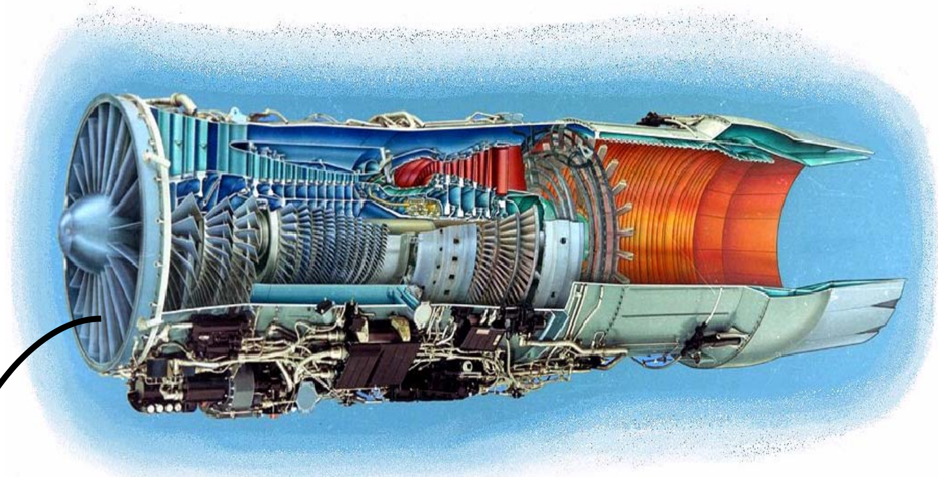
DOE NETL Program Managers: John Fairbanks / Aaron Yocum

Thermoelectric Recovery of Engine Waste Heat at United Technologies

Diesel Engine

Caterpillar

Aircraft Engine



Pratt & Whitney

Waste Heat Recovery

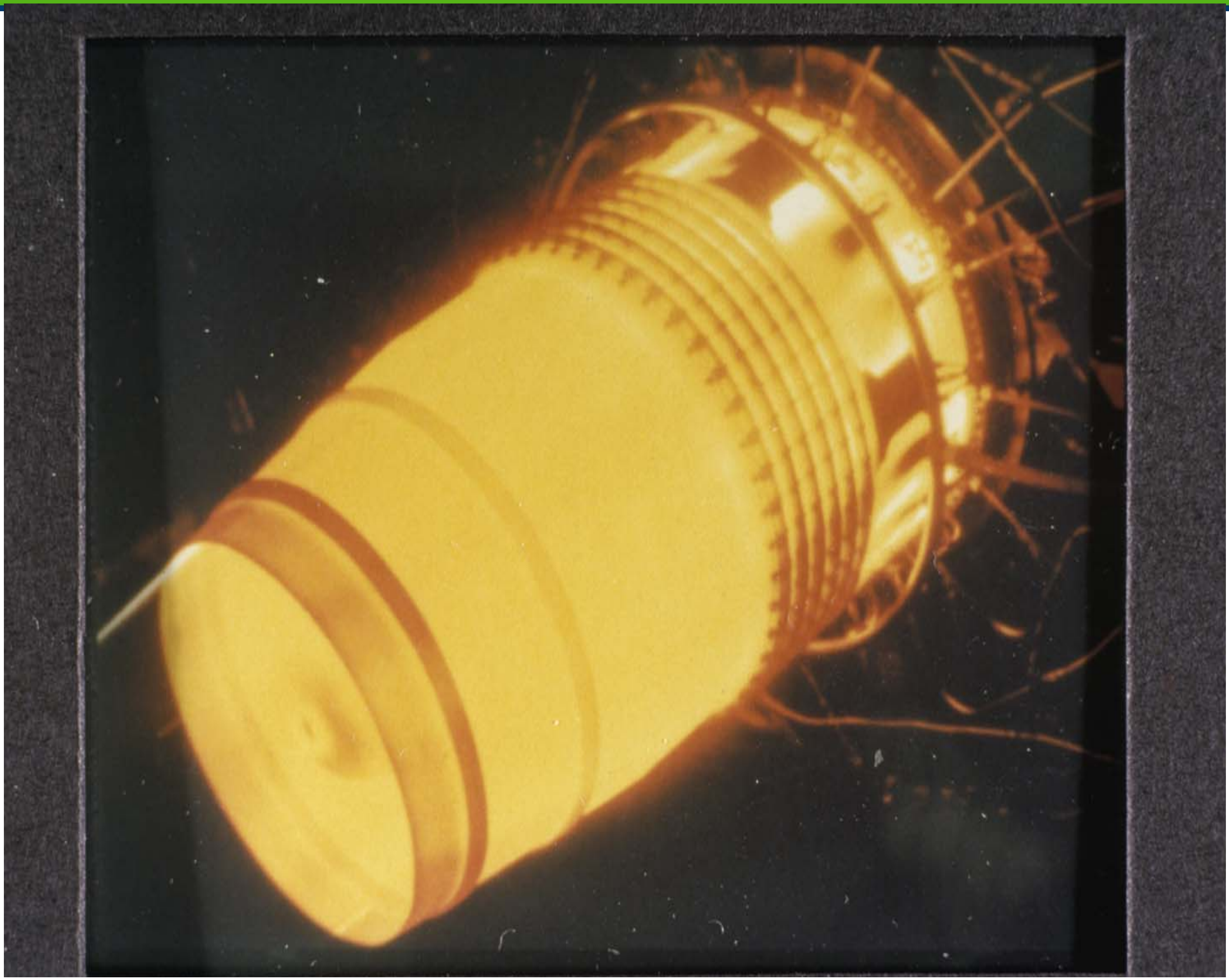
↓

Thermoelectric Solid State Technology

↓

Energy

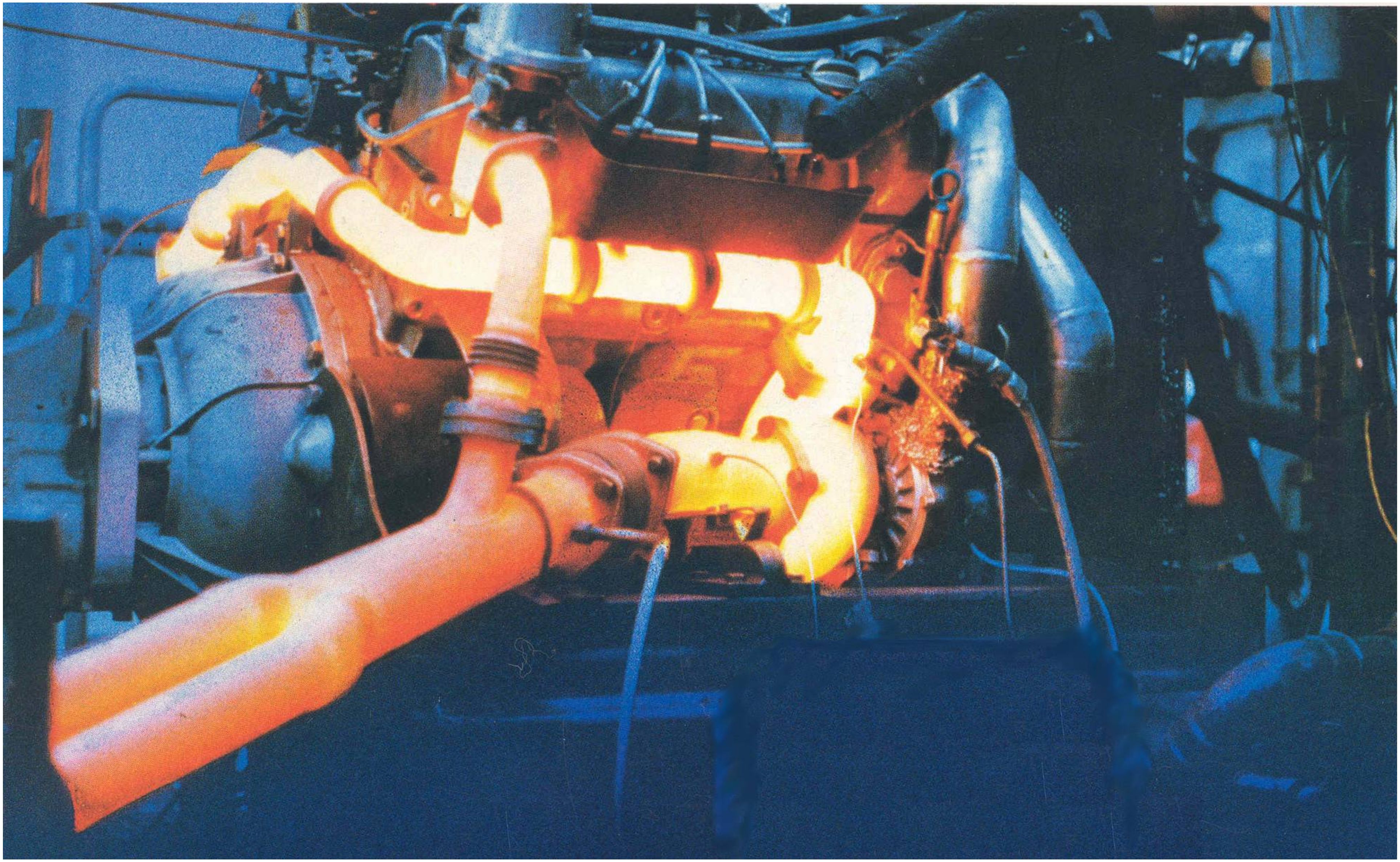
Gas Turbine "Hot Section"



High Efficiency Thermoelectric Teams

General Motor Corporation and General Electric	, University of Michigan, University of South Florida, Oak Ridge National Laboratory, and RTI International
BSST, LLC.	Visteon, BMW-NA, and Marlow, Purdue, UC Santa Cruz, NREL, Teledyne, JPL
United Technologies Corporation	Pratt & Whitney, Hi-Z Technology, Pacific Northwest National Laboratory, and Caterpillar, Inc.
Michigan State University	Jet Propulsion Laboratory, Tellurex and Cummins Engine Company

Available Energy in Engine Exhaust



BSST Team for DOE/NETL Automotive Thermoelectric Generator Project

Primary contributors :

Visteon, BMW and Teledyne

Supporting this technology development:

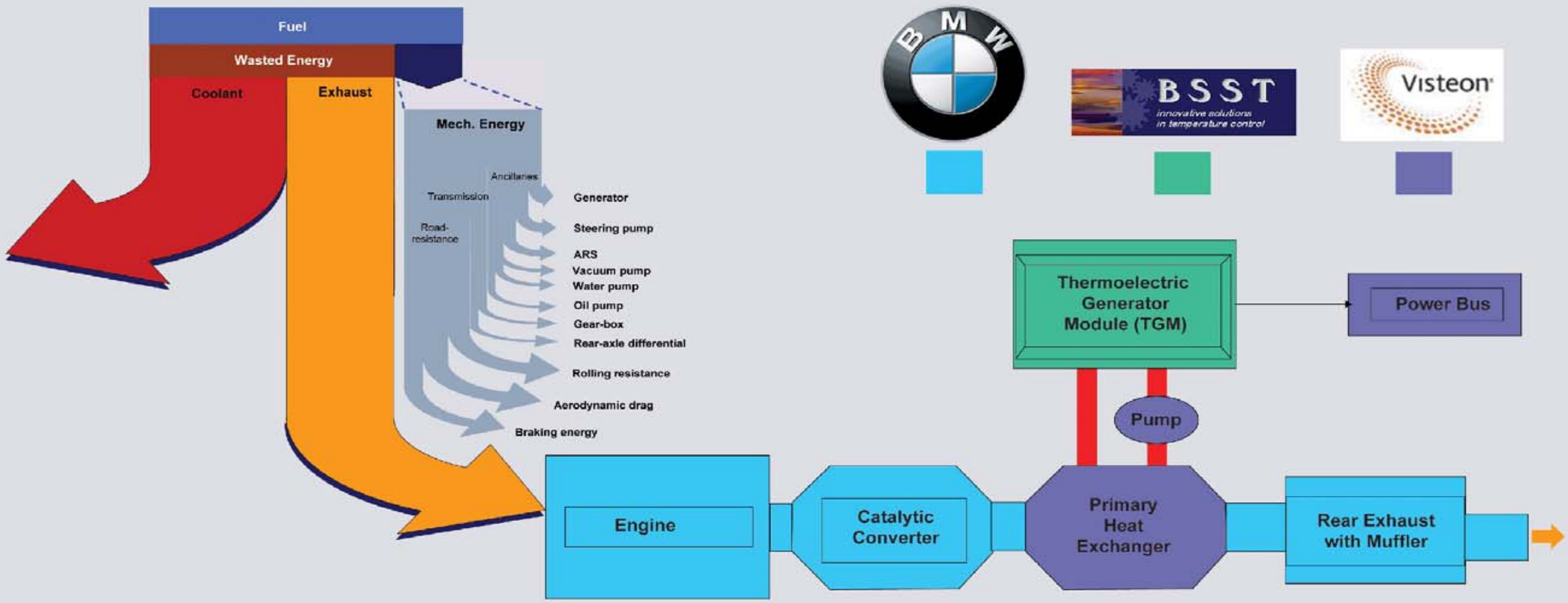
NREL, University of California at Santa Cruz, Purdue University and JPL

BSST's Vehicular Thermoelectric Generator Project

freedomCAR & vehicle technologies program

OBJECTIVE: WASTE HEAT RECOVERY AND CONVERSION TO ELECTRIC ENERGY

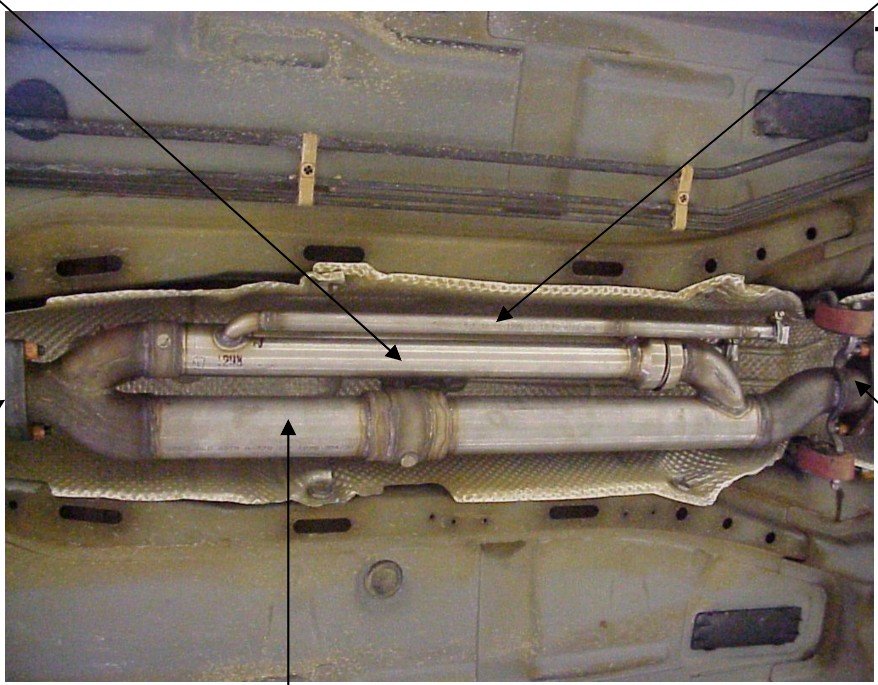
10% Fuel economy improvement by offloading the alternator



Visteon Developed Primary Heat Exchanger

Shell & tube heat exchanger for exhaust gas heat transfer

He/Xe working fluid transports thermal energy to TEG



Cat converter

Muffler

Exhaust gas bypass flow

BSST's 1st Generation Liquid to Liquid Heat Exchanger Design

High power density liquid to liquid heat exchanger

Modeled performance validated through testing

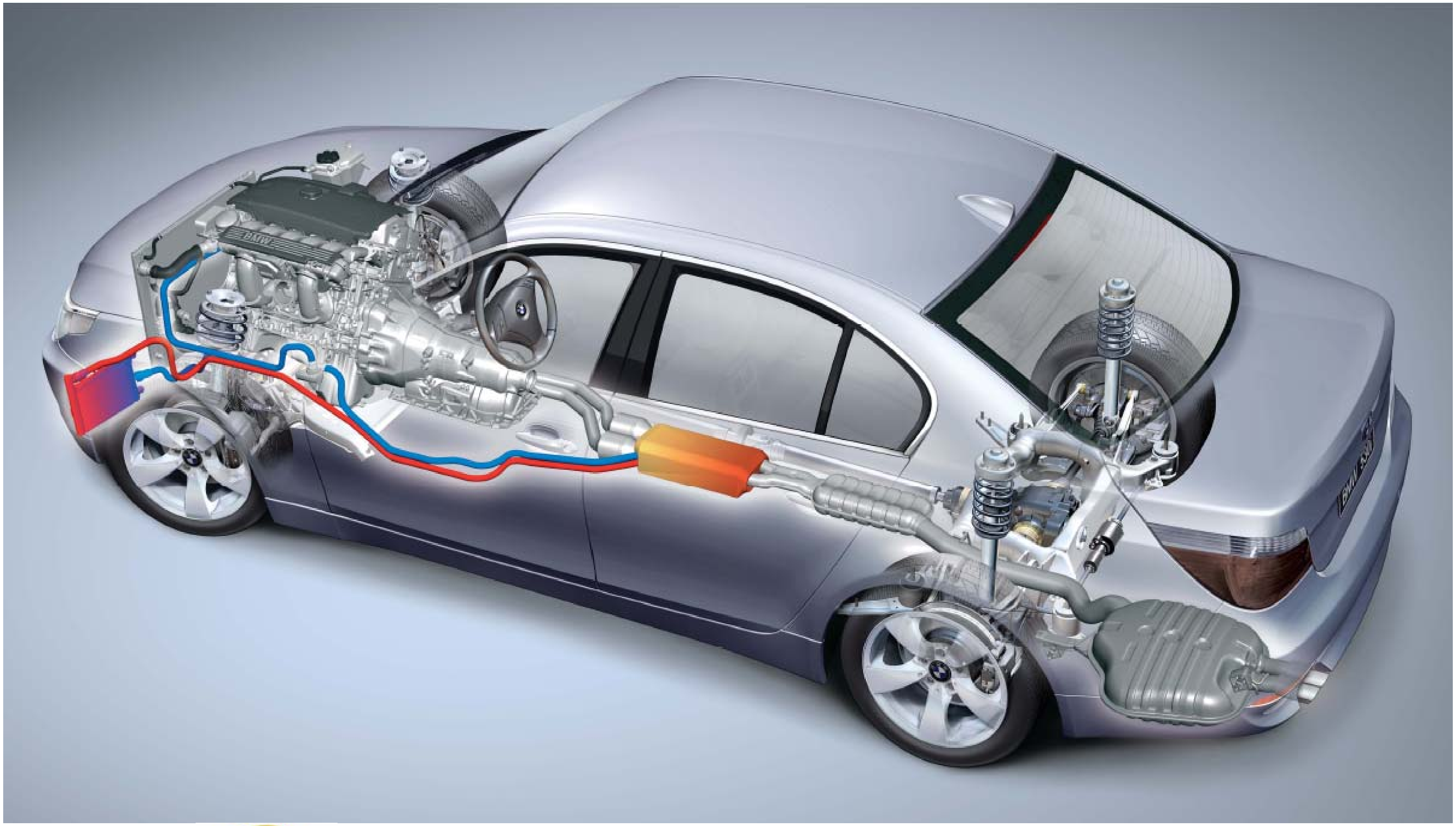
Vehicle / Engine Selection

Selected vehicle platform (BMW 530i, MY2006)

Selected engine platform (Inline 6 cylinder, 3.0 L displacement)

- The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).
- The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe

BMW Series 5 , Model Year 2010, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator



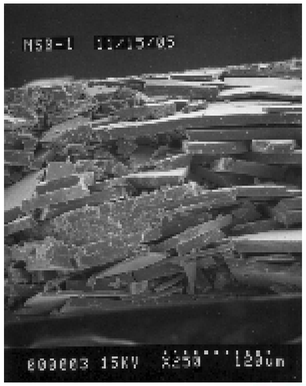
FreedomCAR & Fuel Partnership

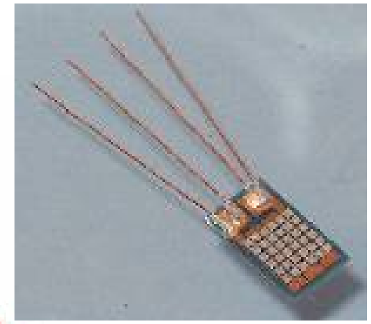
Visteon®

BSST innovative solutions in temperature control

BMW MINI

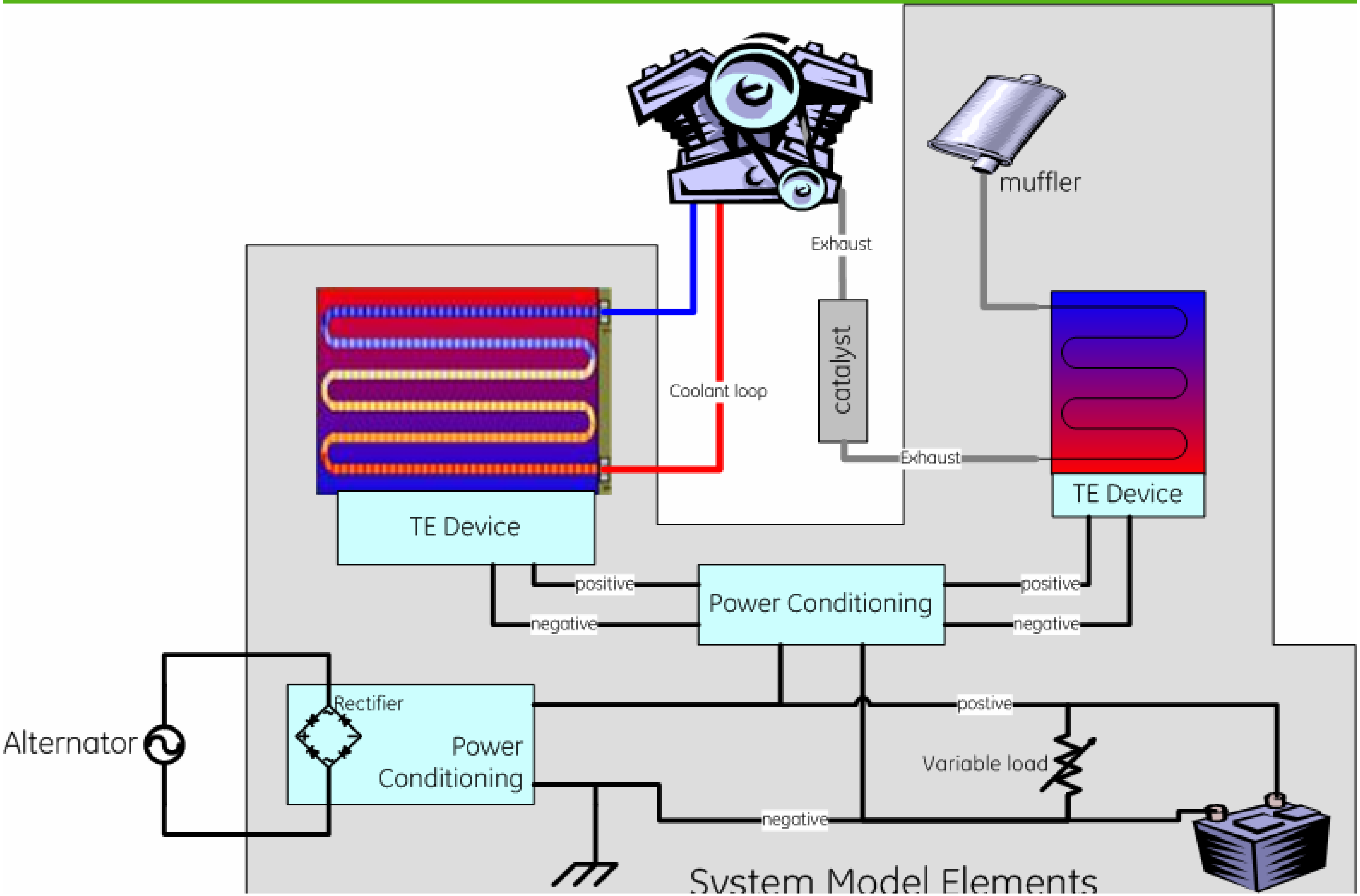
Power Generation Program Goals at RTI



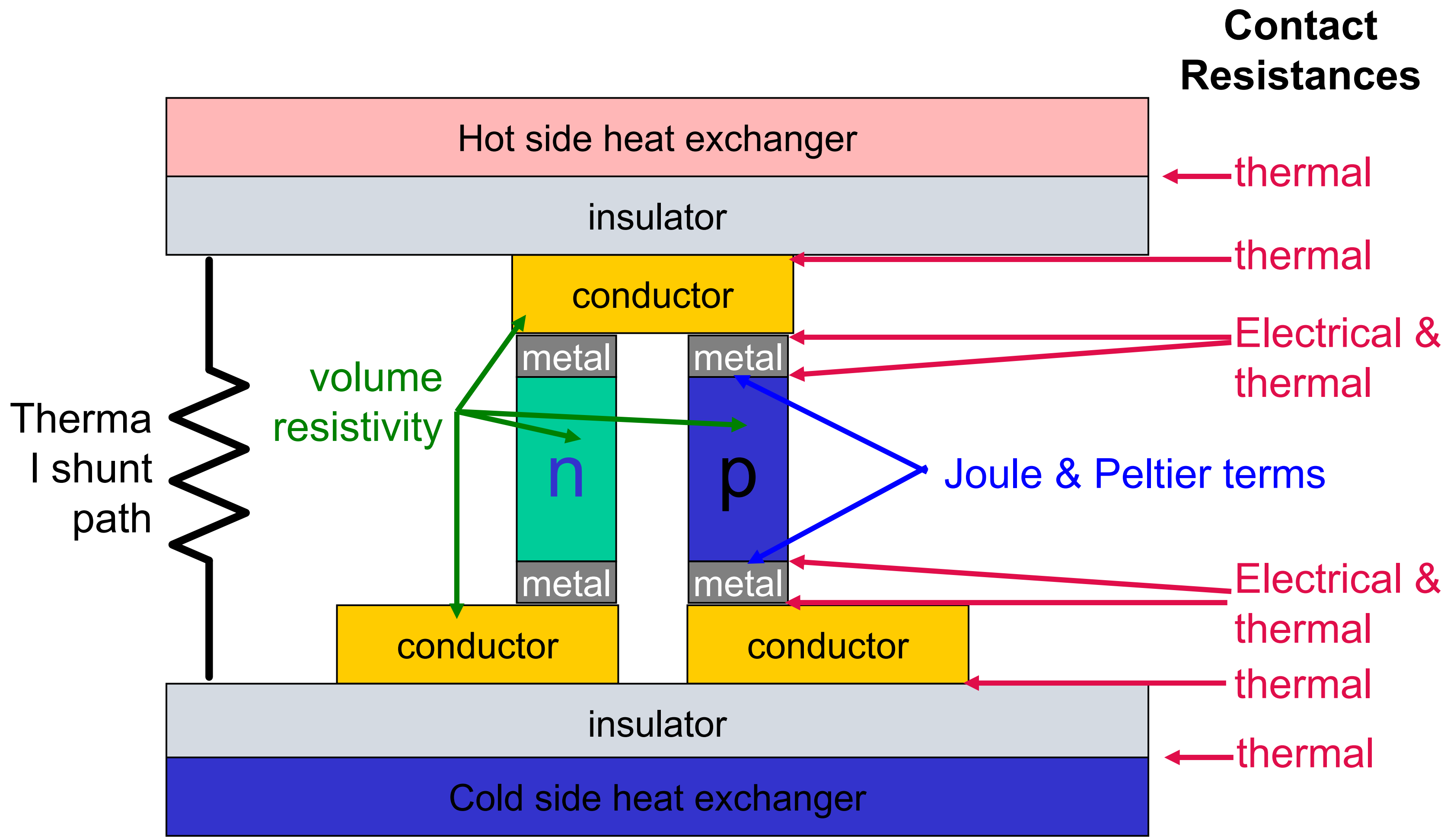


- High performance Bi_2Te_3-based superlattice for radiator-based applications
- High performance bulk Silicon/Germanium, PbTe, and TAGS for exhaust-based applications
- Advanced materials based on nano-structured bulk (NSB) composites

GM's Thermoelectric Generators

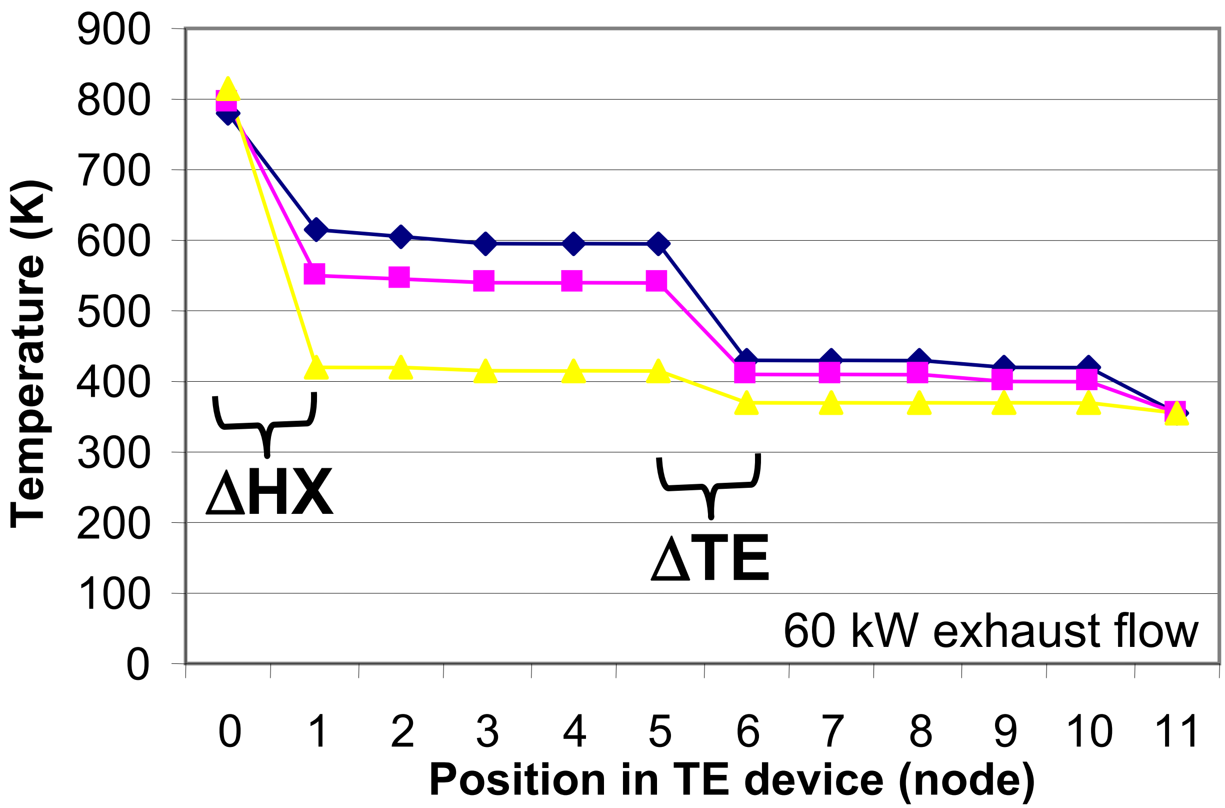


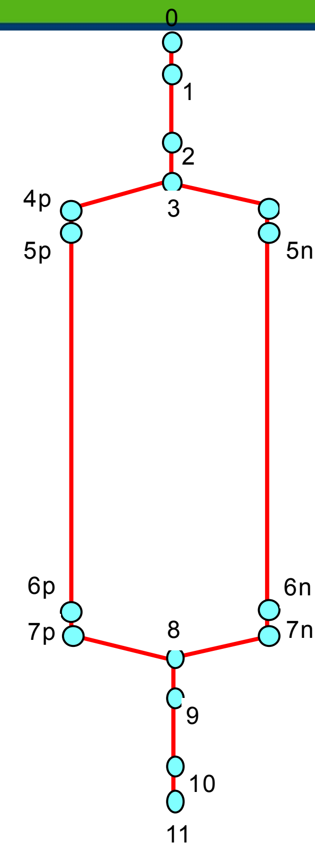
Subsystem Modeling



Joule heating from all electrical contacts are accounted for.

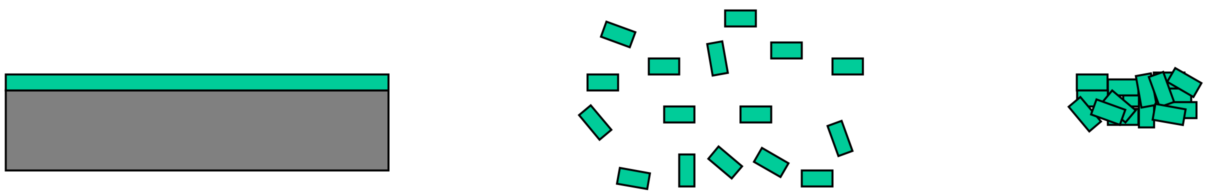
Temperature Profile Through TEG





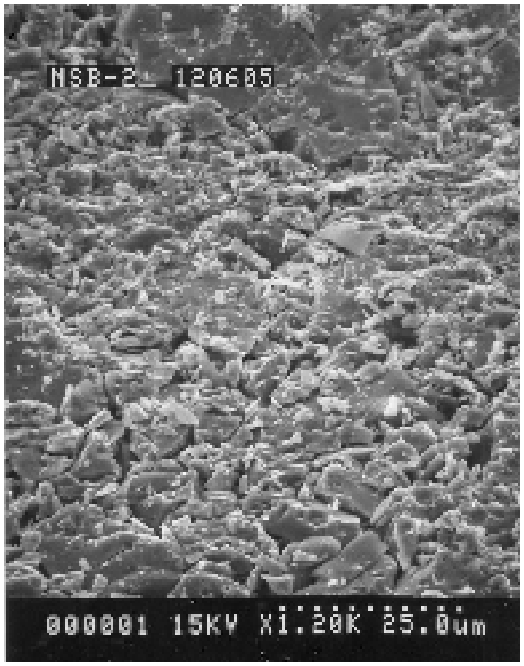
Results indicate hot gas heat transfer is a primary bottleneck

RTI Nano-Structured Bulk (NSB) Materials



- Grow Si/Ge-based SL materials with enhanced ZT
- Remove film while preserving the nanostructure within the particles
- Combine SL film particles to form bulk pellet of enhanced ZT material
- Larger ΔT for NSB potential higher efficiency and more power output.

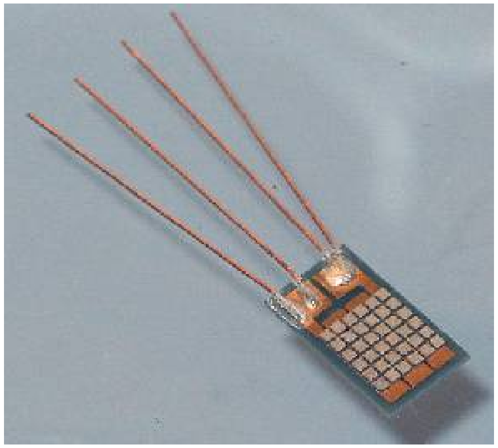
Initial Results from RTI Nano-Structured Bulk Materials

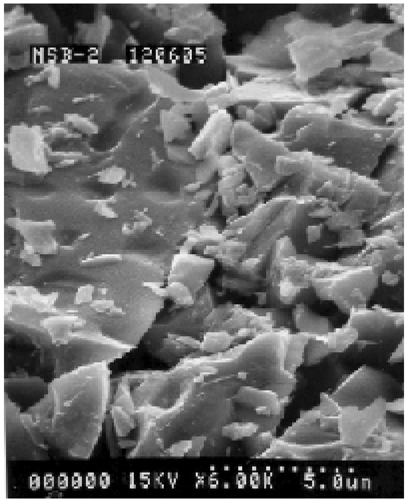


- Films sent to Ames for conglomeration via hot pressing
- A more aggressive cleaning etch composed of HF and HNO_3 was used
- Conglomeration is improving

Highlights of RTI Developments and Future Direction

- RTI SL materials out-perform bulk equivalent with higher ZT and efficiency at ΔT available in automotive applications
- Bulk segmented couples producing >300mW with >8% efficiency (@ΔT_e~ 600°C)
- Bulk couple arrays producing >1 Watt (@ΔT_e~ 600°C)
- Nano-structured bulk material work started with encouraging results – team with GM to enhance conglomeration



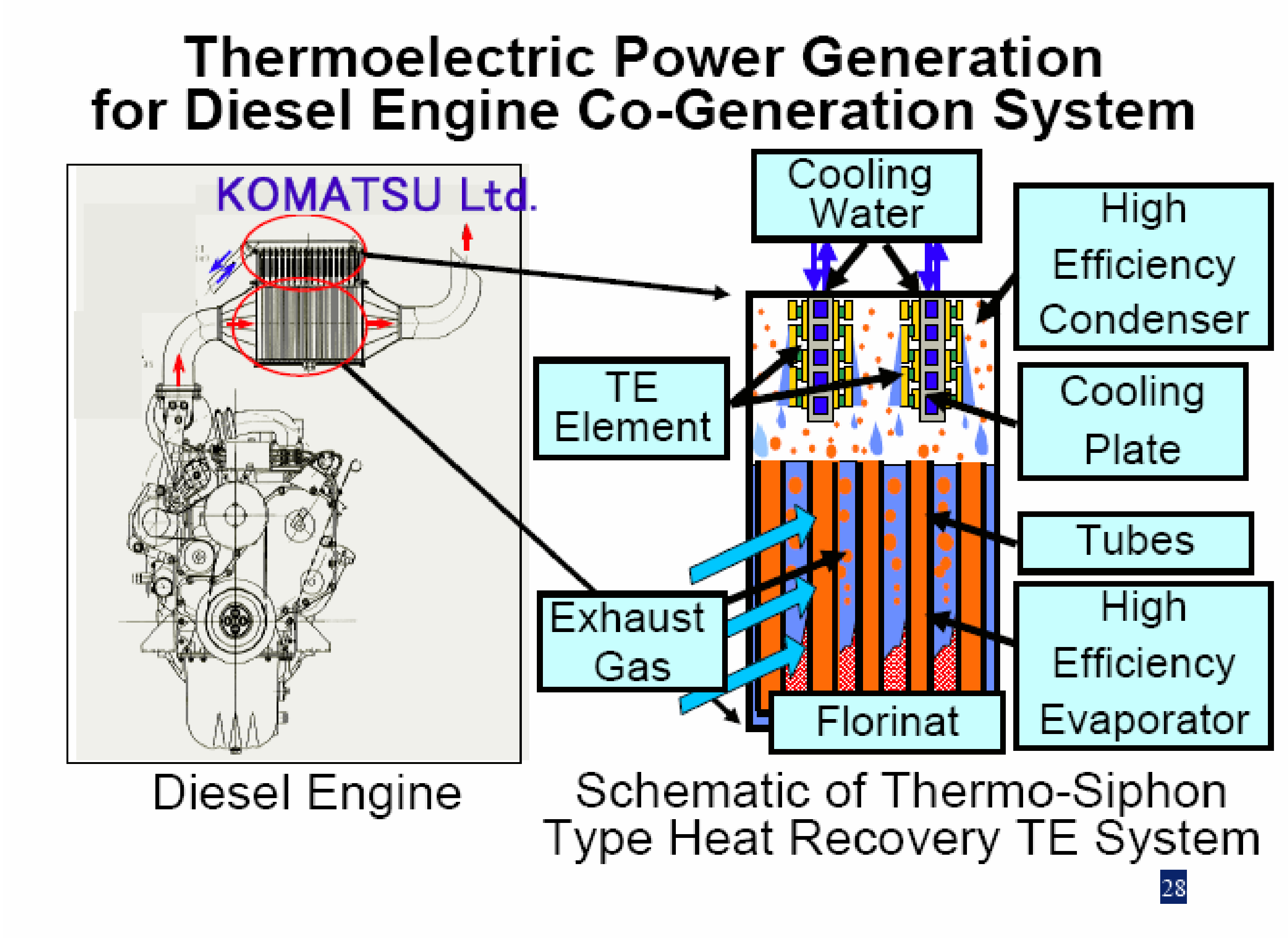


Enabled by DARPA/ONR support

GM Project: Current Efforts at ORNL

- High Temperature Material Testing: RT- 500C
  1. N-type,P-type and undoped Marlow Elements (15)
  2. Skutterudites: GM (4 misch-metal compositions)
  3. Clathrates: USF (5 compositions)
  4. NIST: Half-heusler (HoNiSb)
- Other materials being tested:
  - Oxides: Bulk ORNL, thin film PSU
  - LAST (similar to MSU by GM)

Japanese Vehicular Thermoelectric Generator Program

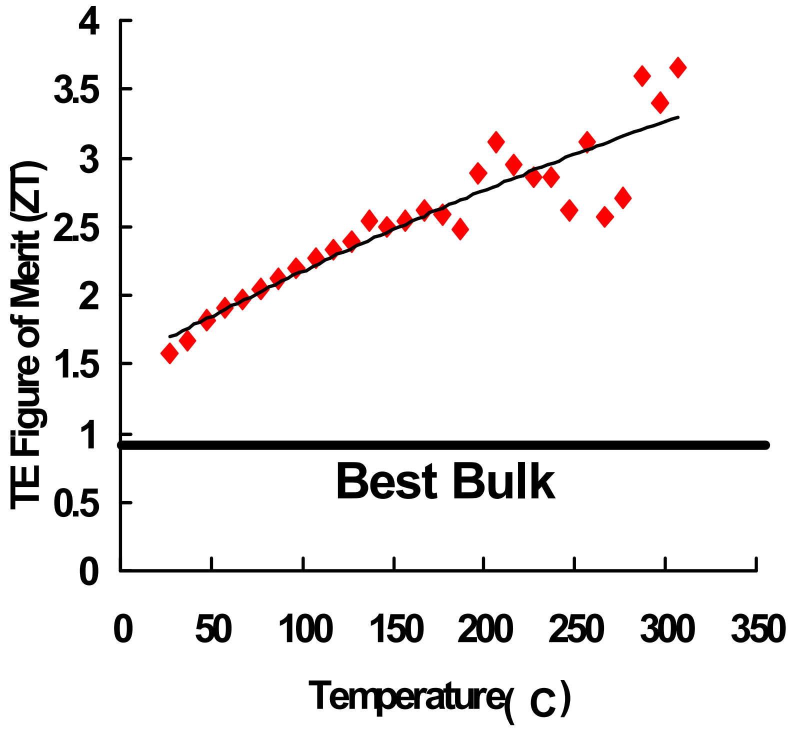


Courtesy of Dr. Takanobu Kajikawa, Project Leader,

Japanese National Project on Development for Advanced Thermoelectrics

Advanced QDSL Thermoelectric Technology
MIT's Lincoln Lab on DARPA/ONR Contract

N-type QDSL TE Performance



Nanostructured QDSL materials greatly improves ZT

U.S. Department of Energy
Energy Efficiency and Renewable Energy
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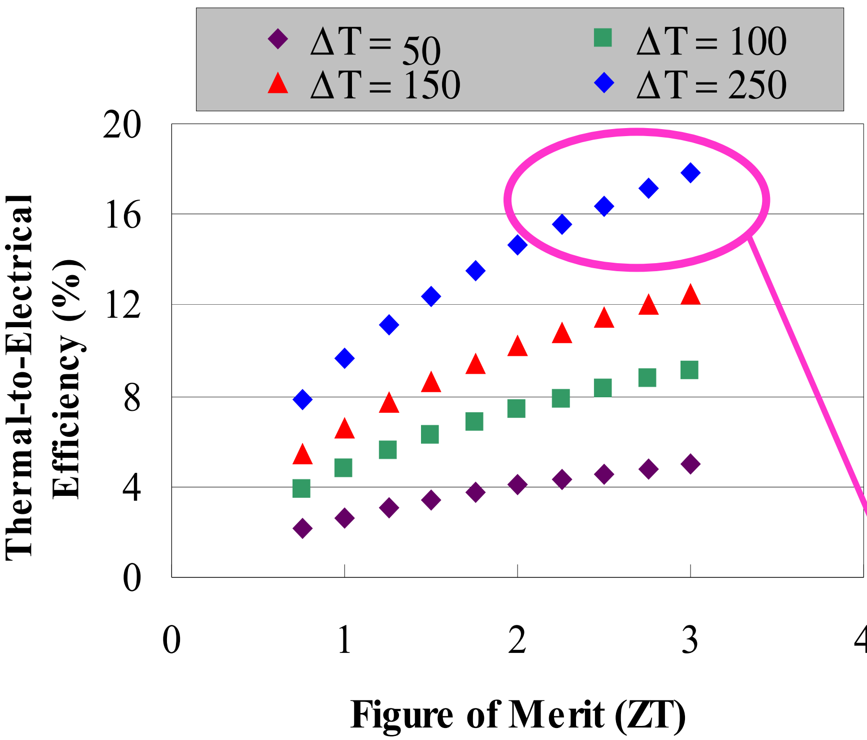
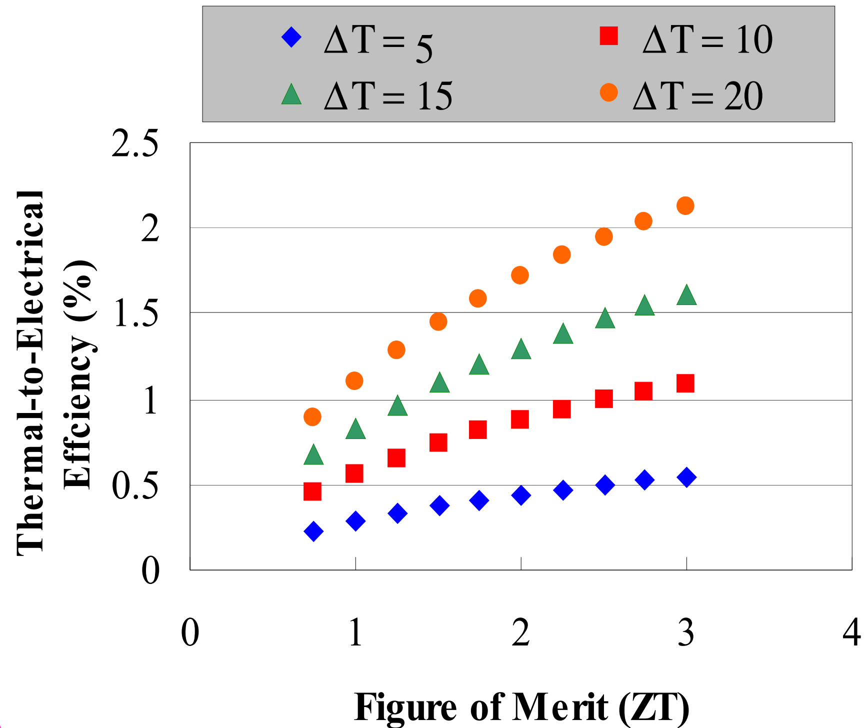
Impact of ZT on Efficiency

Medium-Grade Heat Sources

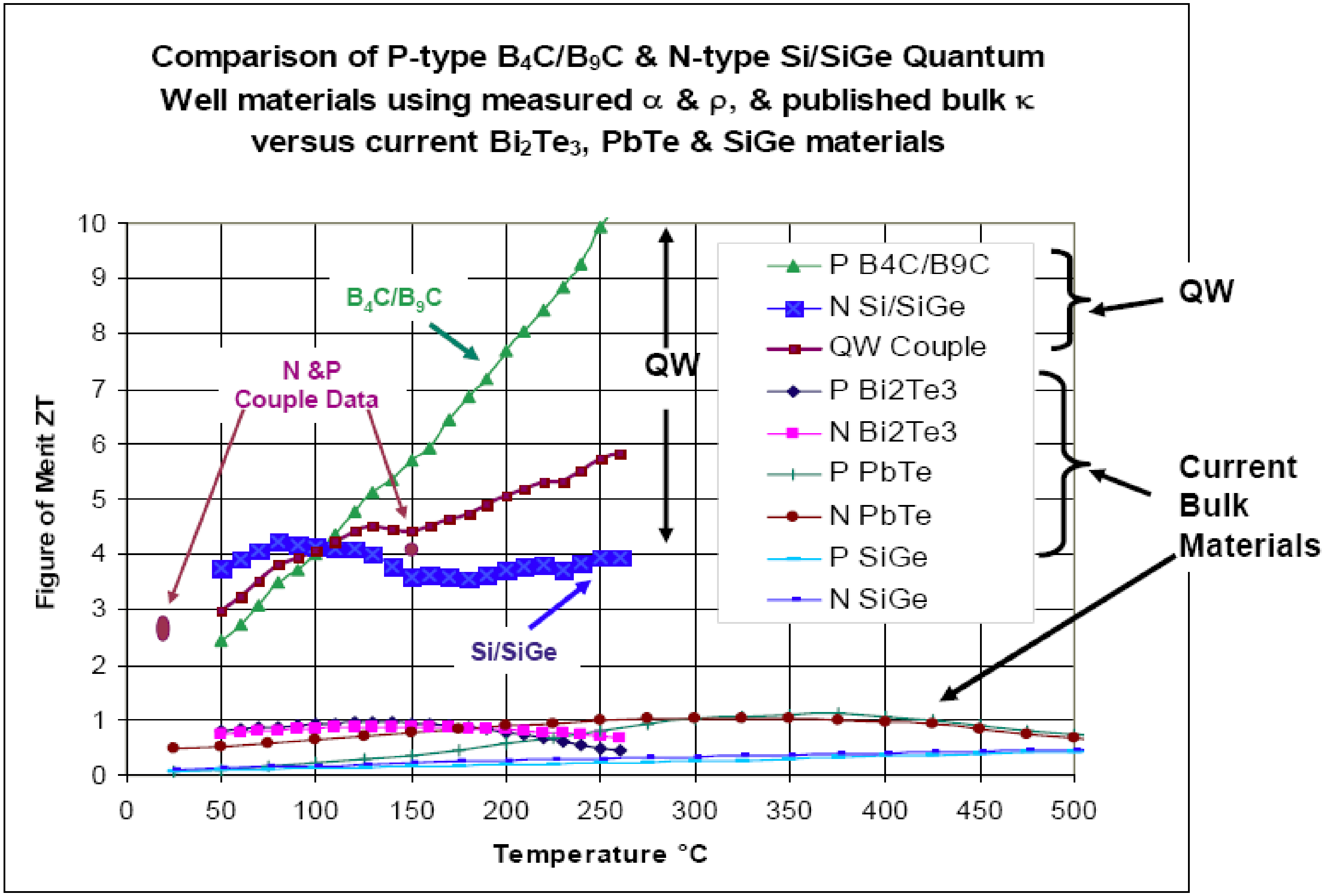


Low-Grade Heat Sources



Exciting for many applications

Advanced Thermoelectrics Figures of Merit



Data: QW & Bi_2Te_3 Hi-Z; PbTe & SiGe JPL Properties Manual

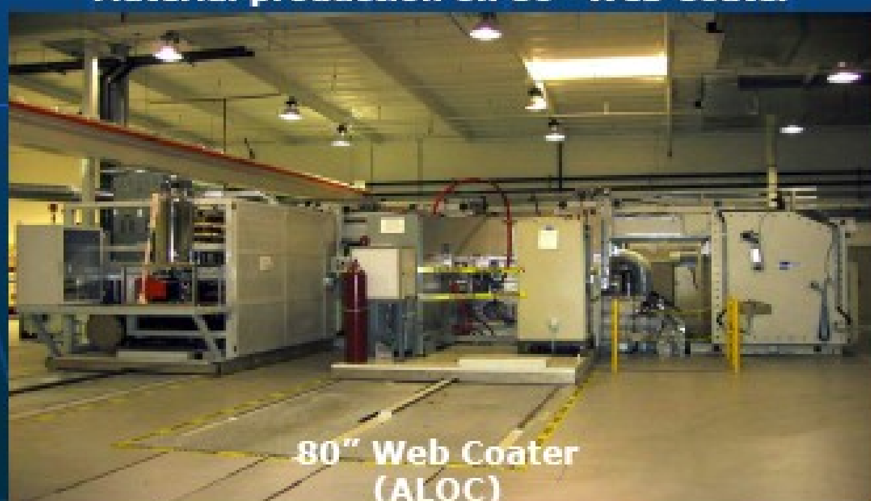
Hi-Z TECHNOLOGY, INC.

General Atomics Sputtering Capabilities

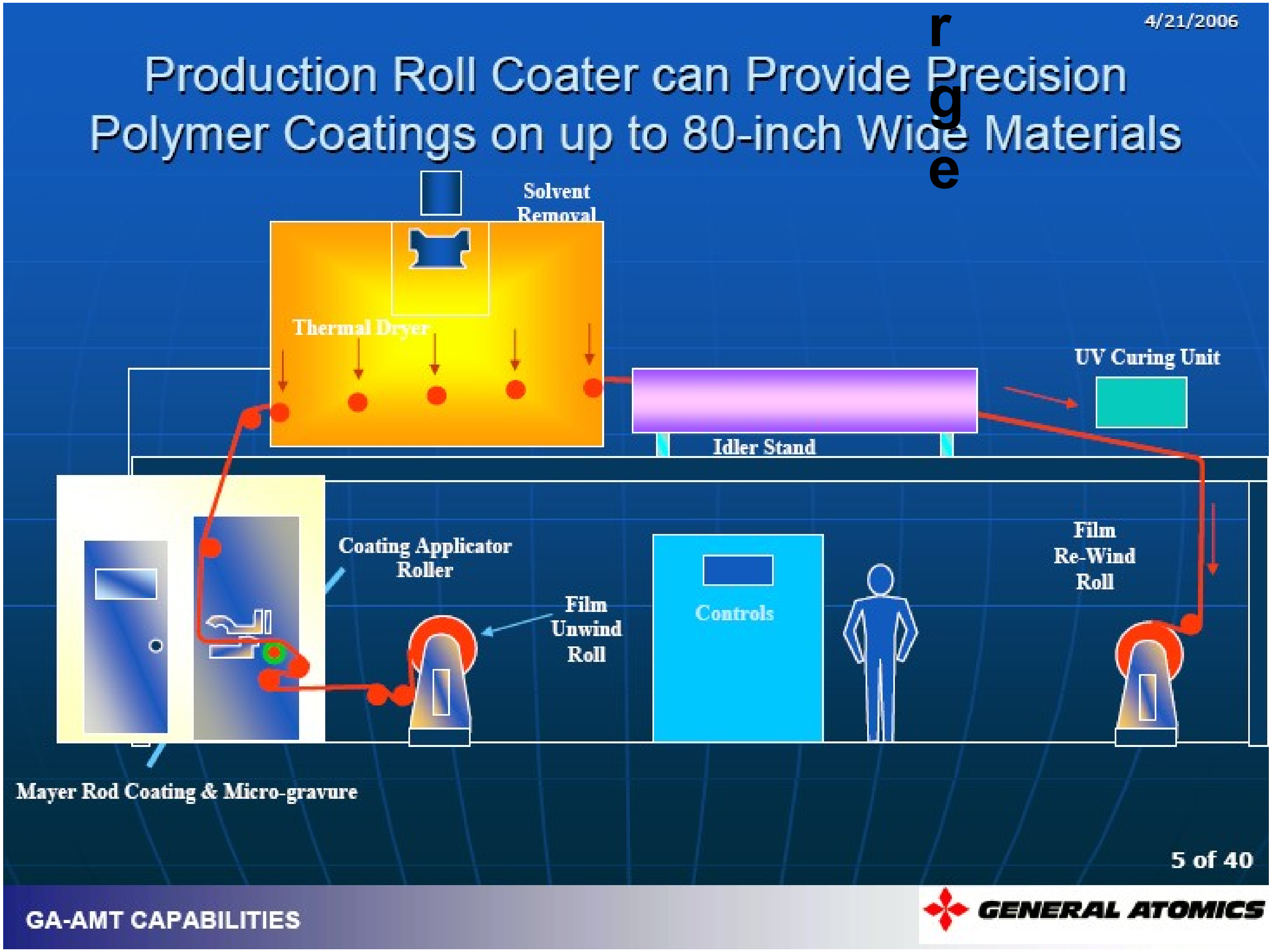
New coatings developed on R&D coater

New products developed on R&D Web Coaters

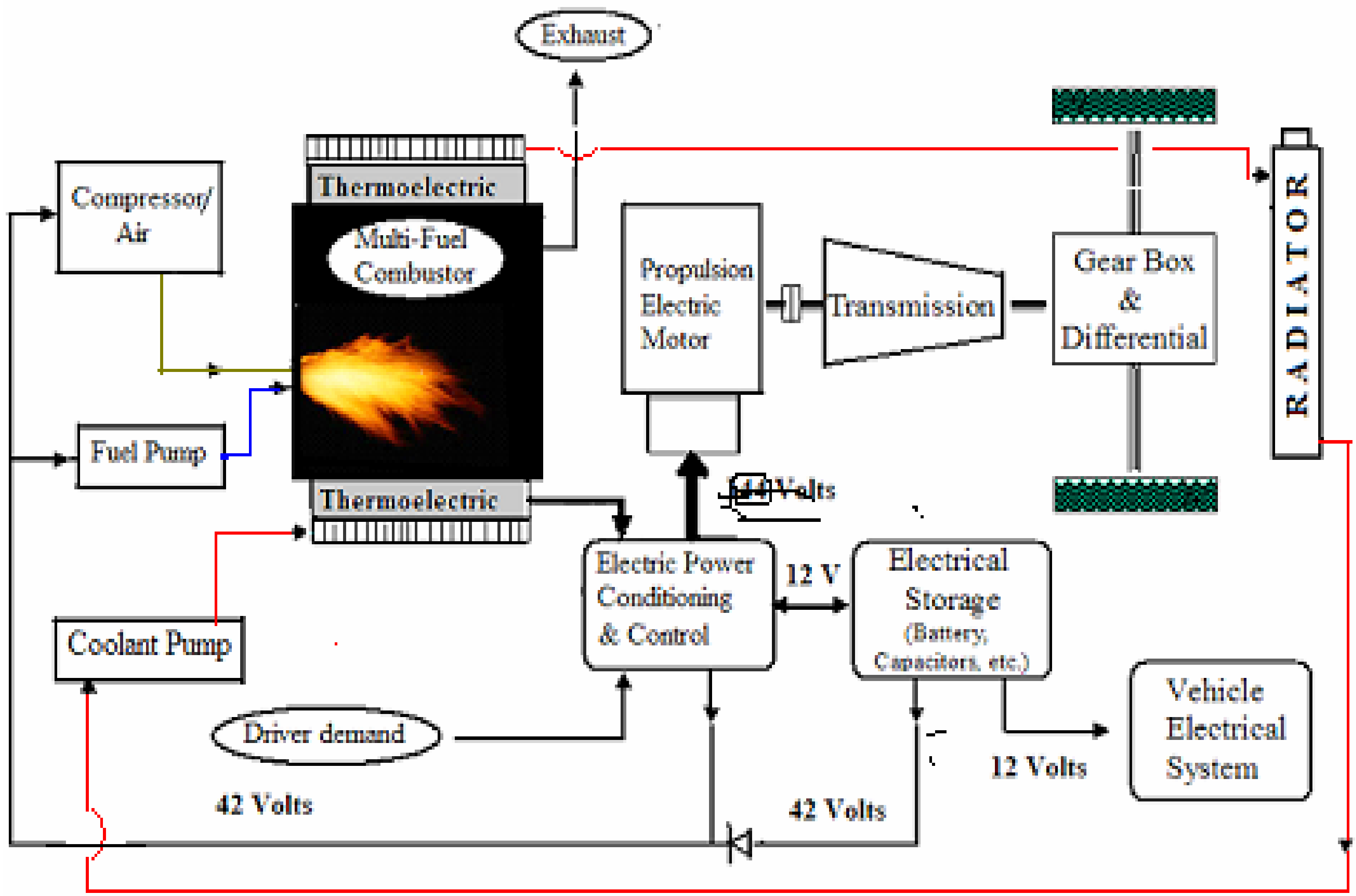
Material production on 80" Web Coater



Large Scale Sputter Coating System



Solid State All-Electric Thermoelectric Hybrid Vehicular Powertrain



Thermoelectric Technology Possibilities for Vehicular Powertrains

Near Term (3-5 yrs)

- Thermoelectric Generator providing 10% fuel economy gain (MPG)
- "Beltless" or more electric engine
- Thermoelectric HVAC (air conditioner/heater) for vehicles

Mid Term (8-12 yrs)

- 2nd Generation Thermoelectric Generators
  - 20 % fuel economy gain auto, light truck (SUV's, Pick-ups and Mini-vans) gasoline engines
  - 16 % fuel economy gain heavy duty trucks

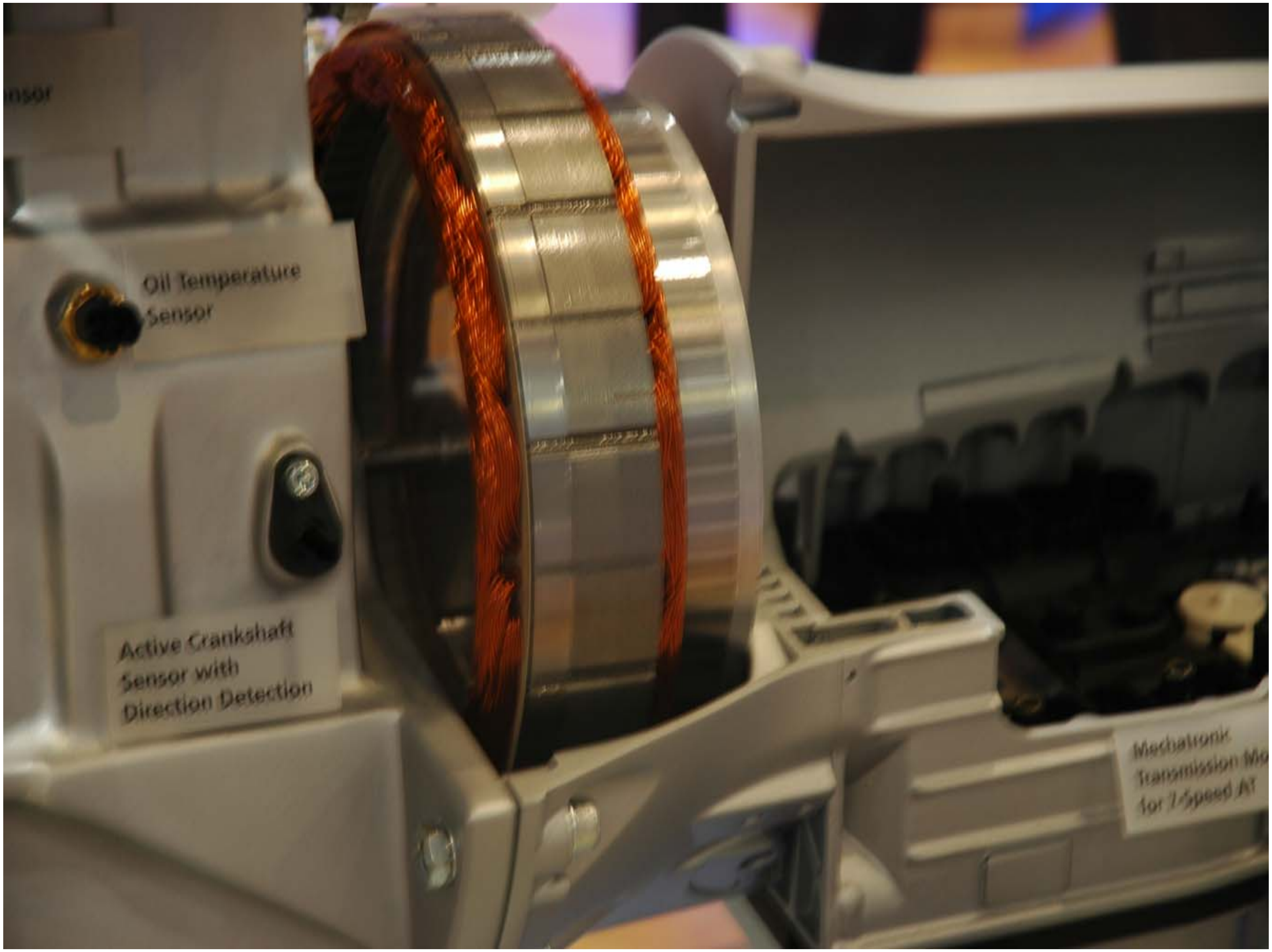
Long Term (12-25 yrs)

- 35% efficient Thermoelectrics with 500 ^{0}C ΔT
  - Replace Internal Combustion Engine
  - Combustor burns any fuel

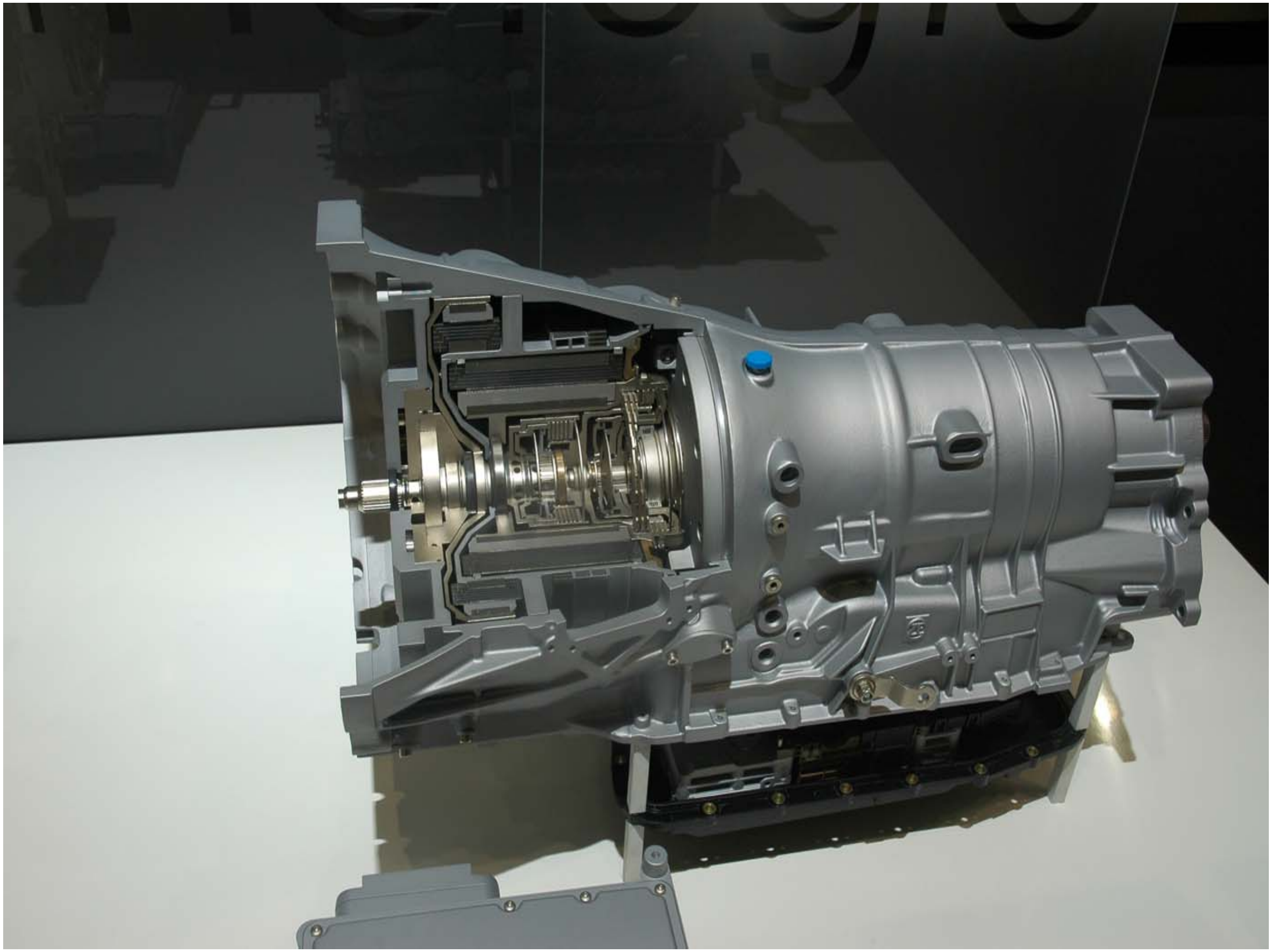
Very Long Term (60+ yrs)

- Radioisotope replaces combustor for vehicle propulsion
  - 30+ years life powertrain
  - Replace vehicle body periodically

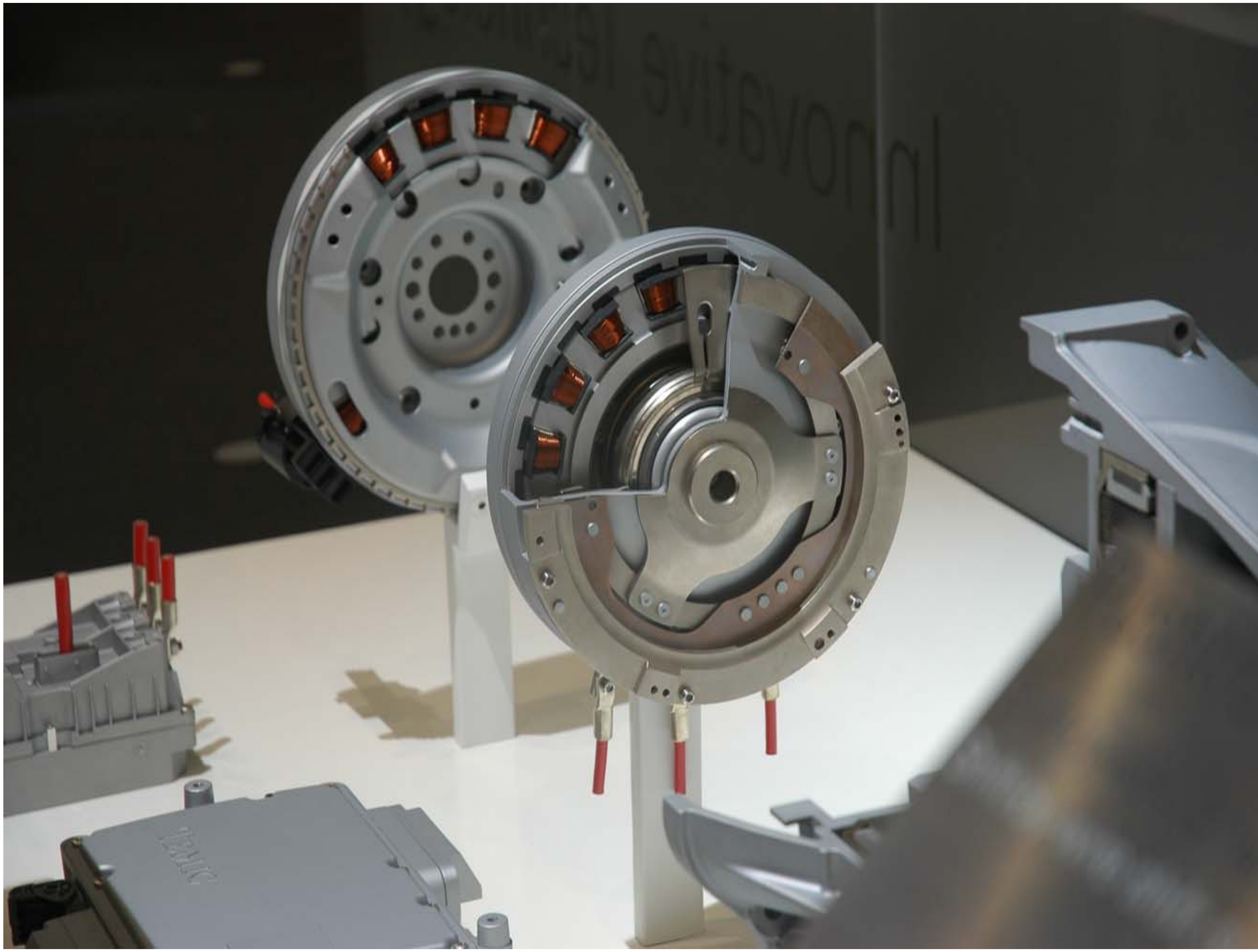
Integrated Alternator/Motor/Starter/Damper



Transmission
Electrical to Mechanical



Electric Motor Drive Wheels
Drive by Wire



Stretch goal for researchers:

- Find thermoelectric materials and system designs that can replace the internal combustion engine
- A system that can convert 25% of its input fuel energy to electric power can **potentially replace some internal combustion engines**
- A system that can convert 50% of its input fuel energy to electric power could potentially replace most gasoline and diesel engines and would even challenge fuel cells.

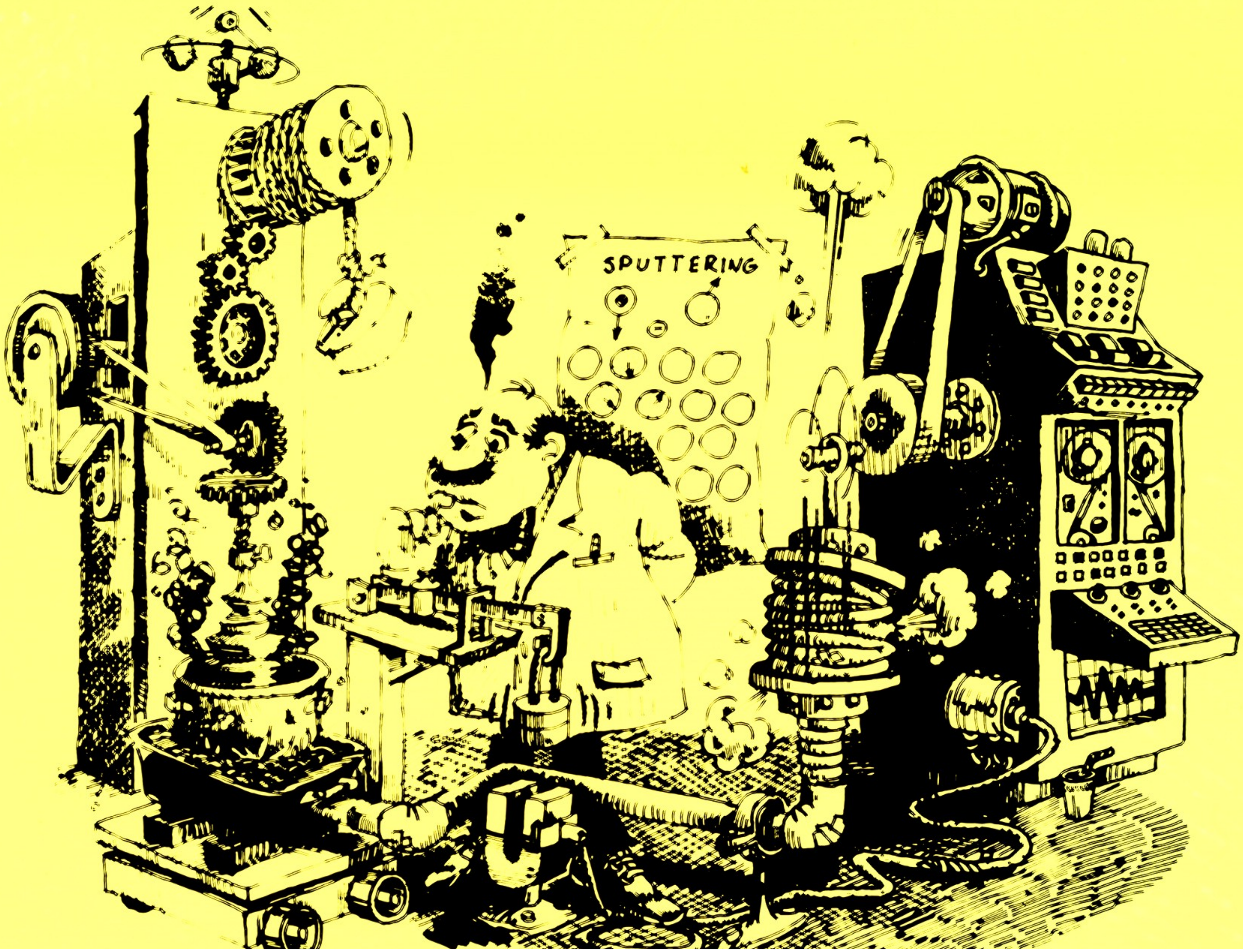
Francis Stabler, GM , MRS 11/28/05

Letter to Editor - MIT Technical Review

- **"If capacity to generate power from heat can be enhanced significantly ………….**
- **No effort should be spared if there is the remotest prospect of realizing such high efficiency devices"**

» Harold Wickes letter 12/05/05 to MIT Technical Review in response to article "Free Power for Cars"

Key : Scale is important



Technical Challenges for Nanoscale Thermoelectrics

- Scale Up to Commercially Viable Thermoelectric Modules
  - Reproduce Lab Scale Microstructure
  - Minimize Contact Resistance
  - Interlayer Diffusion
  - Substrate
    - Provide Structural Support
    - Minimal Thermal Shunt

Measurements

Power Conditioning

Vehicle Integration

Further Fundamental Investigation

NO SHOW STOPPERS AT THIS TIME

Fabrication of Quantum Well Devices

Jack Bass
Hi-Z Technology, Inc.

DEER Meeting, Detroit, Michigan

August 2006

Hi-Z TECHNOLOGY, INC.

Quantum Well Film Comparisons to Current Bi_2Te_3

- Quantum well module with N- and P-type Si/SiGe on Kapton Substrate *vs*
- Current Bi_2Te_3 module at the same geometry and operating conditions ($\Delta T = 200$☜C, heat flux = 10 W/cm^2)
  - 3x power
    - 50 W for QW *vs* 14 W for Bi_2Te_3
  - 7x voltage
    - 12 Volts for QW *vs* 1.7 Volts for Bi_2Te_3
  - 10x higher specific power
    - 2.5 W/gm for QW *vs* 0.2 W/ gm for Bi_2Te_3
  - 10x lower raw materials cost
    - $0.10/Watt for QW *vs* $1.00/Watt for Bi_2Te_3

Hi-Z TECHNOLOGY, INC.

From Quantum Well Films to Thermoelectric Power Module

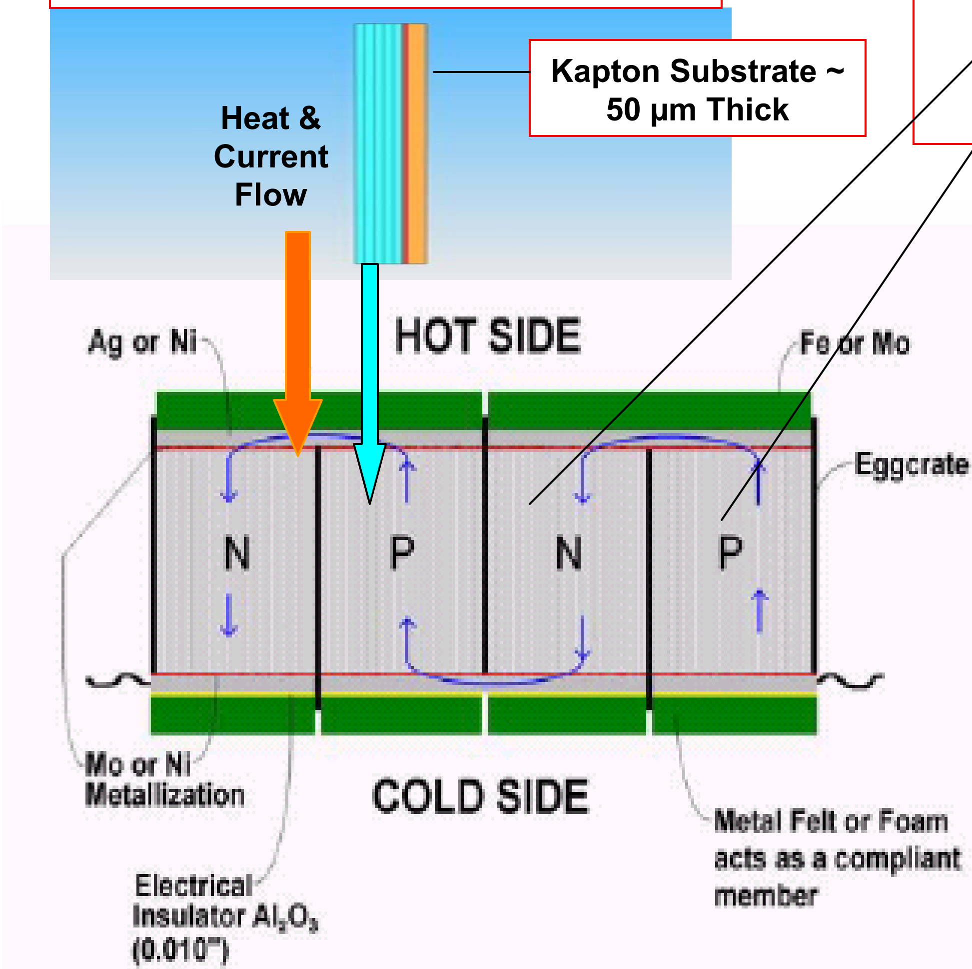
Alternating 10 nanometer Thick Si/SiGe Films Up to 11 µm Thick

Kapton Substrate ~ 50 µm Thick

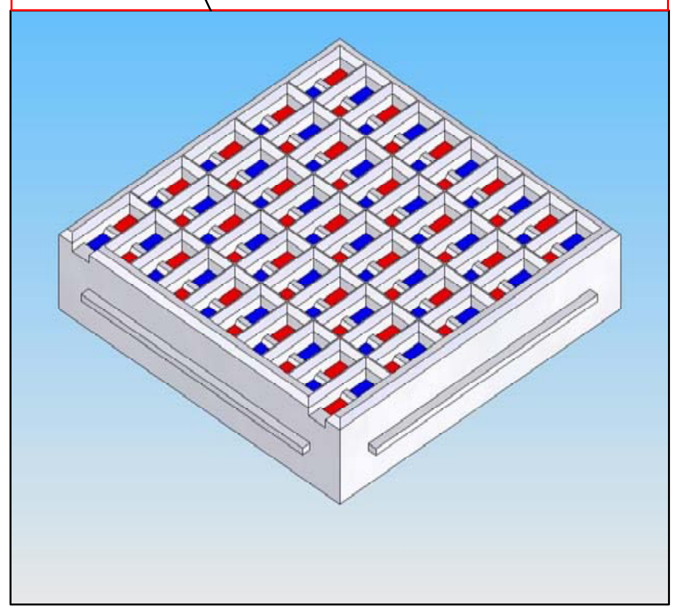
100 films form one TE couple

N element

P element



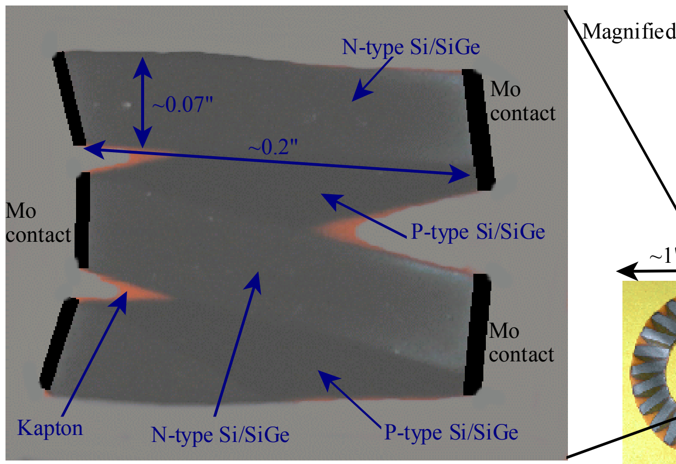
49 TE couples give 50 Watts in 6x6x1 cm TE module at ΔT=200°C



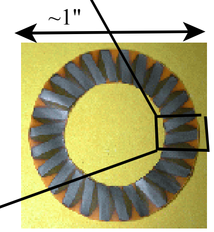
Hi-Z Technology, Inc.

Two Couple Power Producing Device with Si/SiGe Quantum Wells and Mo Contacts on Kapton Substrate Yields Expected Power

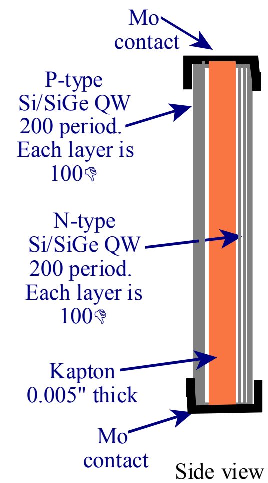
Fabrication Approach



Two couple device with N&P Si/SiGe QW on Kapton substrate



Complete 26 couple device



Results

	Experimental		Calculated	
	2 Couples Measured at ΔT = 40°C	Results 2 Couples Measurements Extrapolated to 26 Couples at ΔT = 40°C	26 Couples at ΔT = 40°C	
T_{COLD} = 26°C T_{HOT} = 66°C			Quantum Wells Si/SiGe with ZT ~ 3.0	Bulk $(Bi,Sb)_2(Se,Te)_3$ With ZT ~ 0.75
Voltage (V_{OC})	225 milli Volt	2.93 V	3V	0.5V
Power	0.371 milli Watt	4.82 milli Watt	5 milli Watt	1.5 mili Watt

Hi-Z TECHNOLOGY, INC.

Quantum Well Film Materials Summary

Quantum well TE material for 50 Watt module

- 0.32 m^2 with 11 micron multilayer film thickness
- Volume 3.5 cm^3
  - Based on ΔT = 200☜C, heat flux = 10 W/cm^2 gives » 64 cm^2/Watt
  - Area/volume reduced with higher TΔ and heat flux
  - Raw materials
    - Si $37.20/kg
    - Ge $956.30 /kg
    - B $94.15/kg
    - C $16.10/kg
- 5µ Si substrates: $15,128.25/$m^2$
- Sputtered 2 µ Si on 1 Mil Kapton: $21.14/$m^2$
- High volume cost for QW TE module: ~0.20/Watt

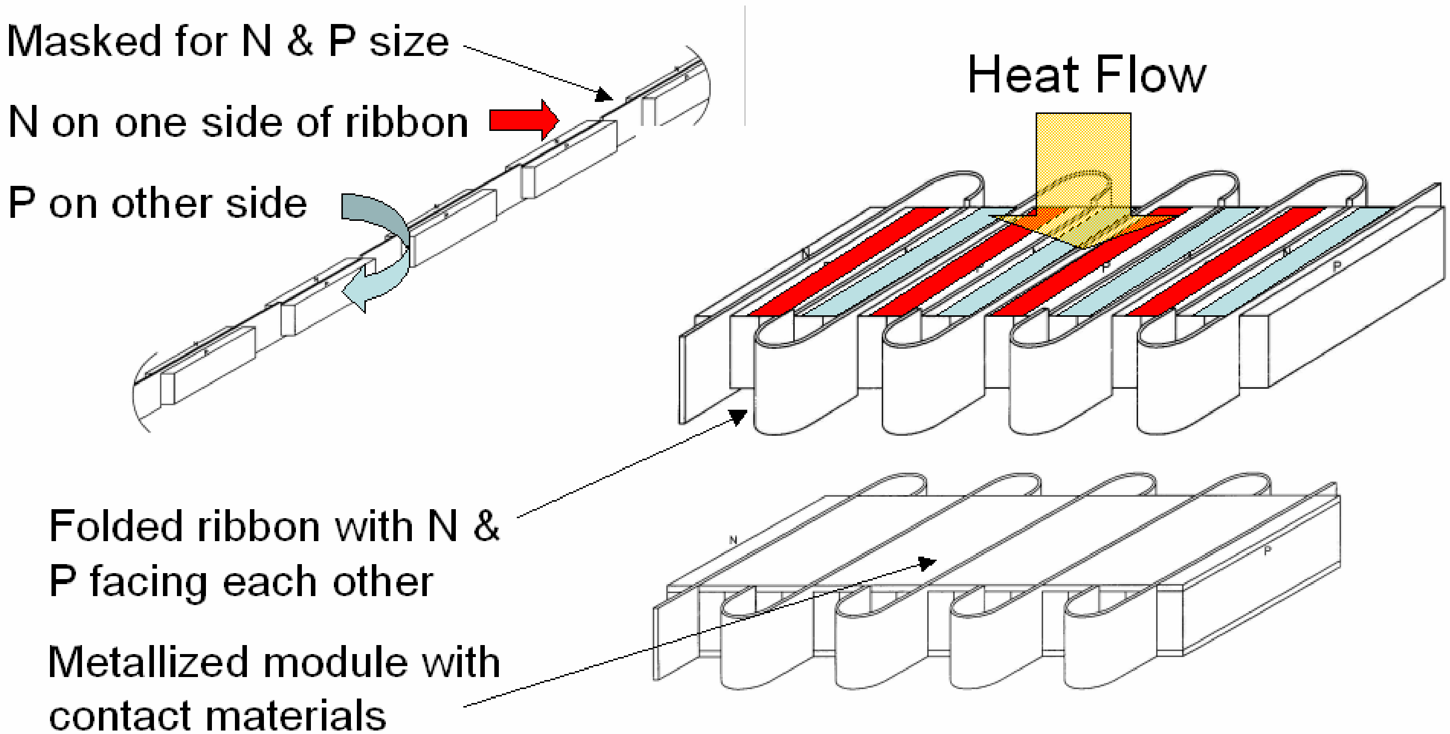
Hi-Z TECHNOLOGY, INC.

Large Area Sputtering Leads to Rapid TE Module Assembly

Process Change - Folded Quantum Well Module

Sputtering process forms module & eliminates eggcrate

Improves efficiency and reduces costs



Hi-Z TECHNOLOGY, INC.

Path to Commercialization for Quantum Well Thermoelectrics

Dr. Lawrence Woolf

General Atomics

San Diego, CA

Presented at the

2006 Diesel Engine-Efficiency and Emissions Research Conference

Detroit, Michigan

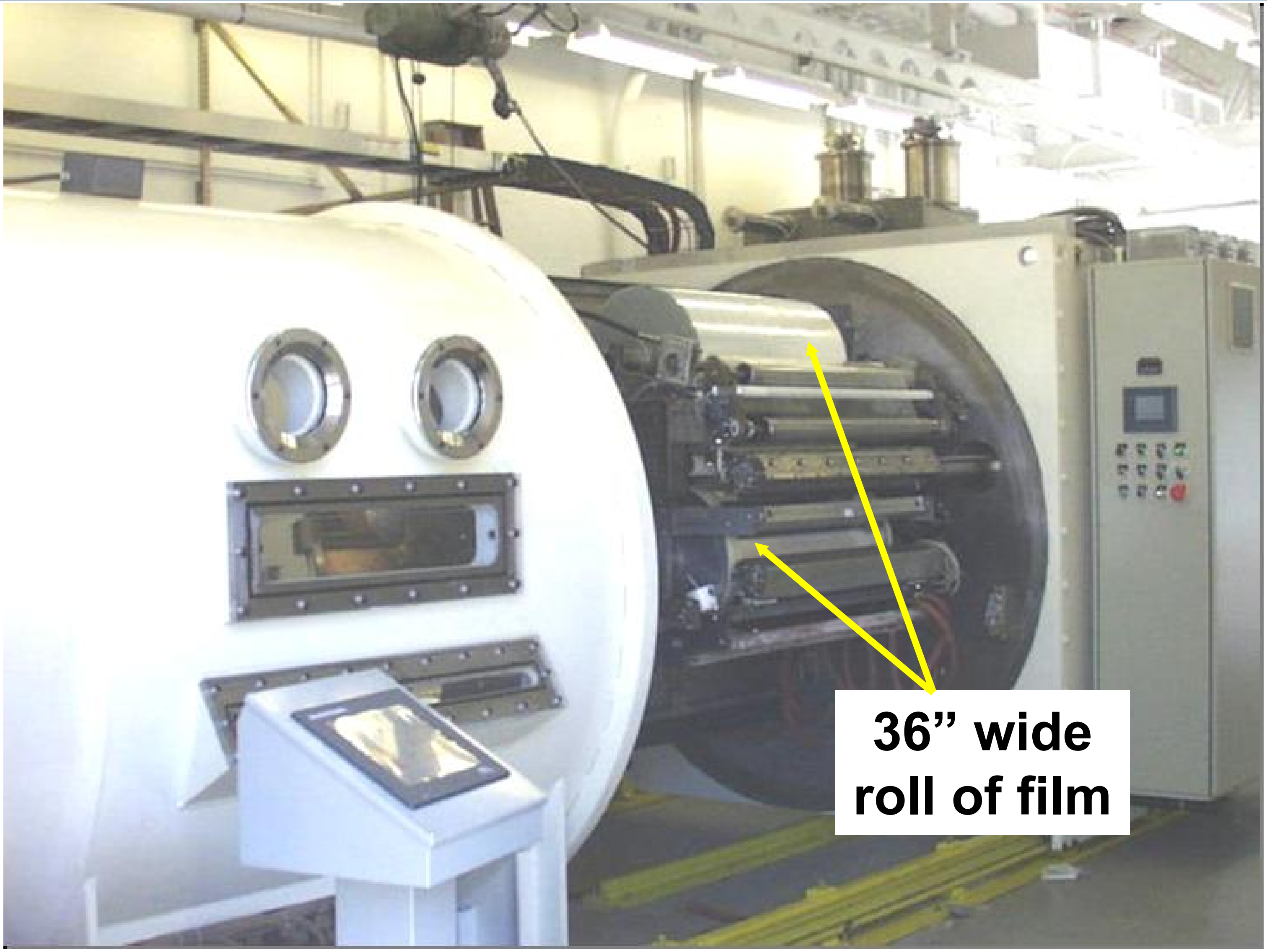
August 24, 2006

GENERAL ATOMICS

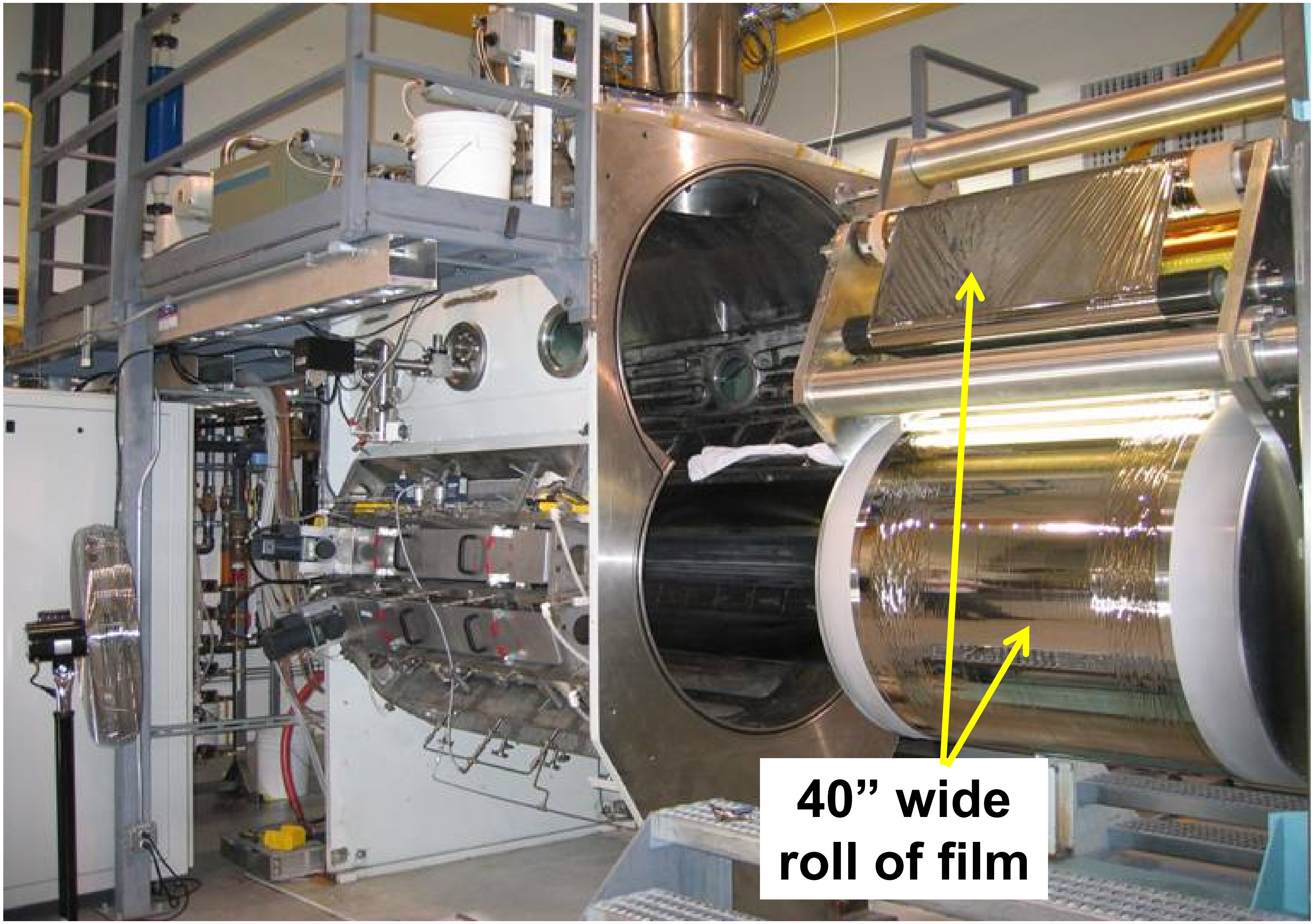
A path to commercialization currently exists

- **High rate sputtering on plastic films**
  - "Web coating"
- **Large-area, high-rate sputtering systems exist and are currently in use**
- **Kilometer-length rolls of meter-wide plastic film are continuously sputter coated in large vacuum chambers**

General Atomics 36” wide film coater



General Atomics 40” wide film coater



General Atomics 2.2-meter (80”) wide film coater

Si/Si-Ge QWTE: path to commercialization

Issue	*State of Art*
Material	Si is commonly used
Coating rate	1 µm thick at 100 m^2/hr 10 nm thick at 10,000 m^2/hr
Coating cost for 200 10 nm layers (2 µm total)	~$15/$m^2$
Reproducibility/uniformity	~1%
Film length	0.5-5 km
Film width	1- 2.2 m

Scale-Up Challenges

Issue	Problem	Solution
Thermal treatment	Coatings require 300-900 °C	Heat treatment during or after deposition
Substrate	Width, cost, temperature	Kapton-1.2m, $6/m^2, 400°C Proprietary substrates
Stress	Coatings > few microns can crack	Process optimization Need to validate
Processing	100-1000 layers	Requires high quality film handling (~50 layers done)
TE Properties	Achievable in large scale/high rate	Need to validate
B-C films	Large area sputtering uncommon	Need to validate

A path to commercialization currently exists:

High rate continuous sputtering onto plastic films