THERMOELECTRIC POWER GENERATION

ARPA-E Small Engines Workshop, May 2014

Scope:

- Historical perspective
- Technology basics
  - Materials
  - Devices
- Today's applications
- Commercialization potential

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SUMMARY – THERMOELECTRIC GENERATORS

Highlights

- High reliability due to minimum of moving parts
- Field-proven in space and terrestrial apps
- Well-suited for autonomous applications
- Industry push to low cost materials, devices and production methods

Concerns

- Material level efficiency in 6-10% range in WHR applications
- System level efficiency in 1-3% range
- Usage of scarce elements
- Low production volumes
- Slow progress in material improvement

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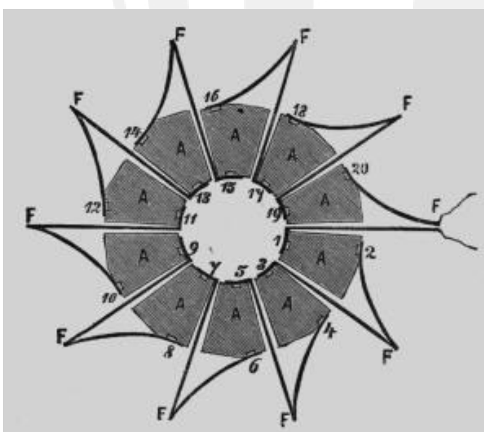
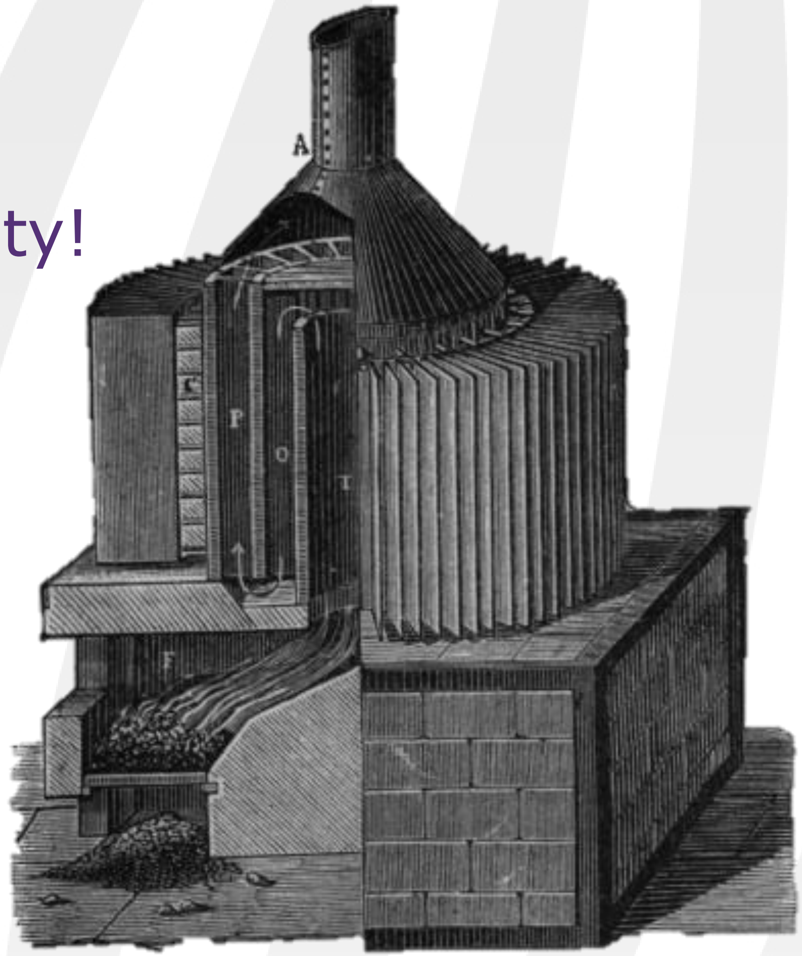
HISTORICAL PERSPECTIVE

THERMOELECTRICS – AN OLD KID ON THE BLOCK

- Late XIX century – electroplating needs electricity!
- Heat source: gas or coke
- Material system: ZnSb/Fe



Top view of electrical circuit



192 Watts, at 54 Volts and 3.5 Amps

http://www.douglas-self.com/MUSEUM/POWER/thermoelectric/thermoelectric.htm

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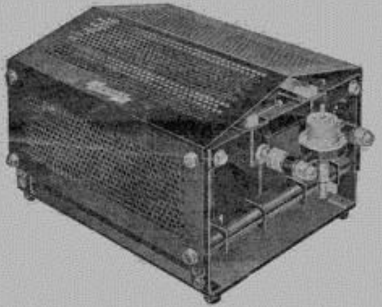
RELIABLE AUTONOMOUS POWER

GAS Operated RADIO !

THE INVENTION OF
A GENERATION



THIS IS
THE THERMO-ELECTRIC GENERATOR
which makes your Battery Set Independent of Batteries of any kind. Dispense with Accumulator charging and uncertainty of Reception. Gas, unfailing in supply will definitely improve your listening

THE HOME GENERATING STATION

PROVIDES THE FOLLOWING ADVANTAGES

- Improved Reception—No background Interference—No failure through rundown Batteries—Gas supply always available
- Automatic Control—A governor regulates gas supply and amount of current generated according to volume required
- Dispenses with cost of Battery replacements and re-charging

Gas will never let you down. You may have been disappointed and inconvenienced in the past through lack of battery power when your favourite programme was broadcast. This cannot happen if you install a GAS GENERATOR

You are invited to "listen in" to Gas Radio at our St. John Square Showrooms

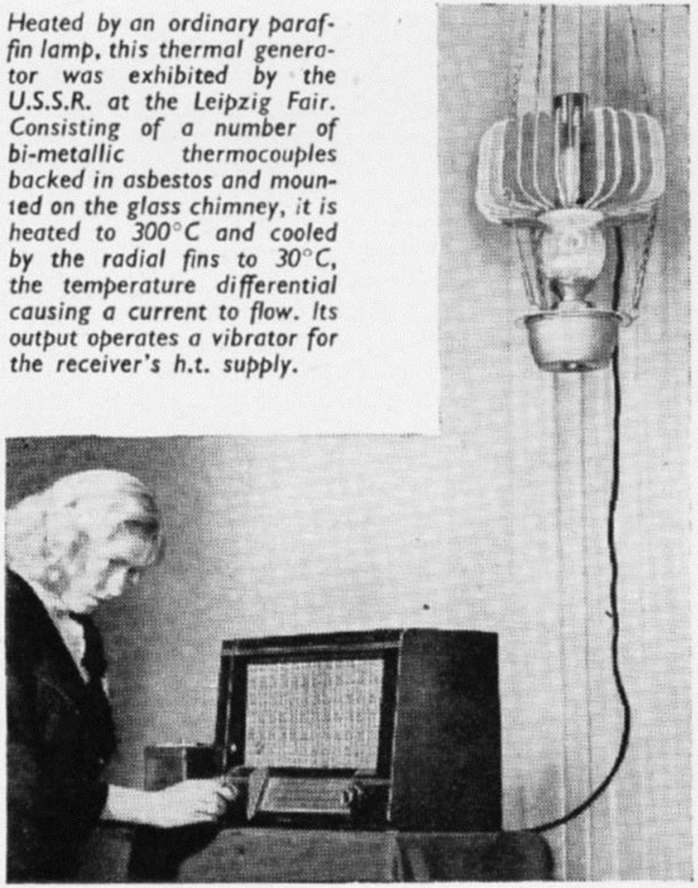
ECONOMICAL. INEXPENSIVE. DEPENDABLE.
EASILY INSTALLED. CAN BE FITTED UP TO 70 FEET AWAY FROM YOUR SET

The Cardiff Gas Light & Coke Co.

Chief Office and Showrooms	BUTE TERRACE
City Showrooms & Ladies' Rest Room	ST. JOHN SQUARE
Penarth Showroom -	STANWELL ROAD
Whitchurch Showroom -	CHURCH ROAD

THERMO-ELECTRIC RECEIVER

Heated by an ordinary paraffin lamp, this thermal generator was exhibited by the U.S.S.R. at the Leipzig Fair. Consisting of a number of bi-metallic thermocouples backed in asbestos and mounted on the glass chimney, it is heated to 300°C and cooled by the radial fins to 30°C, the temperature differential causing a current to flow. Its output operates a vibrator for the receiver's h.t. supply.



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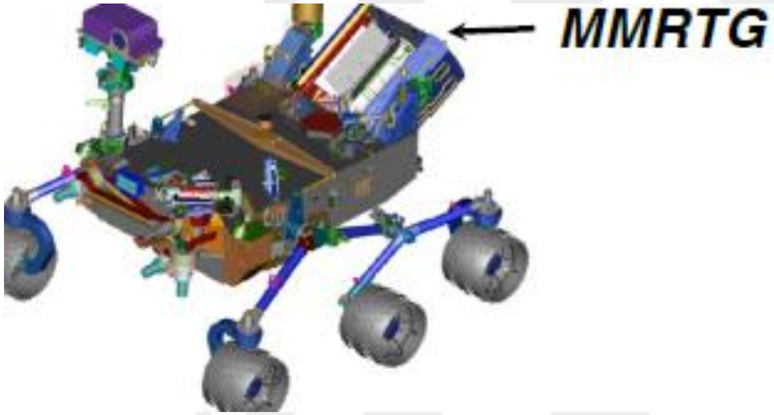
TODAY'S APPLICATIONS



Curiosity Mars lander, ~120 W TEG
(all spacecraft flying beyond Mars uses a TEG)

Gas-powered TEG for remote generation of electricity along pipelines, up to 500 W per unit

Water heater or gas furnace pilot light control
750 mV, ~50 mW
30 mV, ~10 mW

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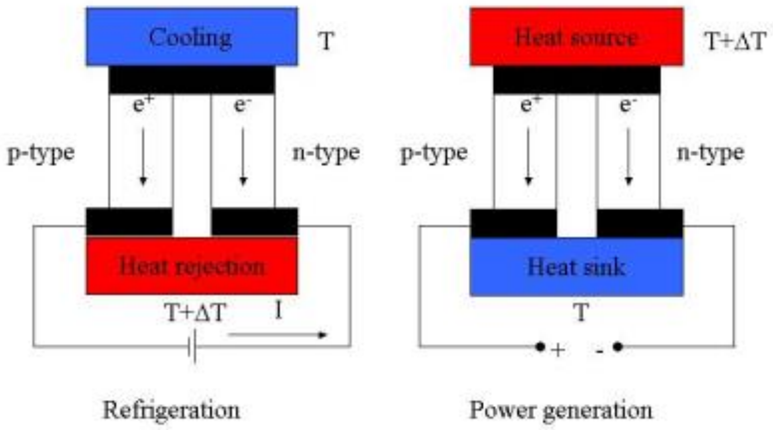
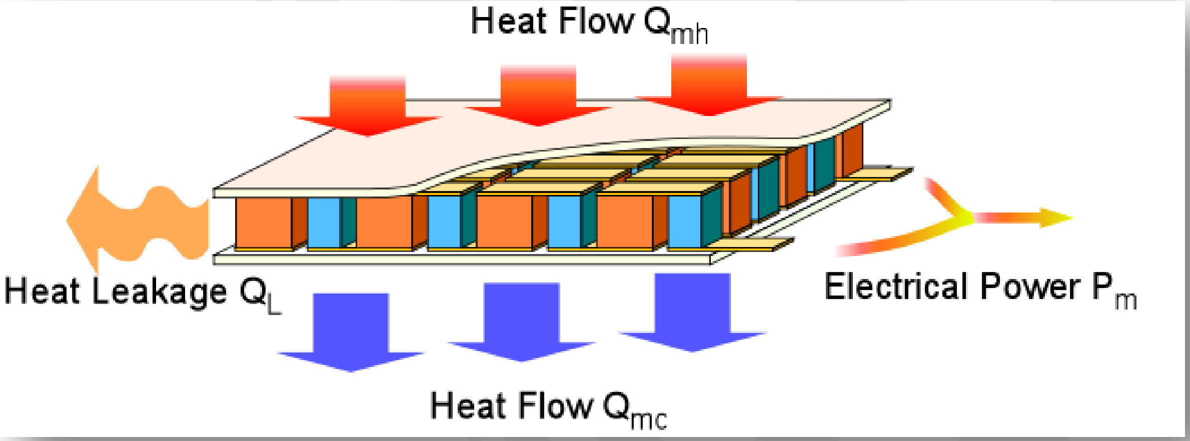
TECHNOLOGY BASICS

CONVERSION OF HEAT TO POWER



- solid state effect
- compound semiconductors are most efficient
- materials judged by figure of merit, Z, preferring:
  - Low thermal conductivity
  - High electrical conductivity
  - High thermo EMF (Seebeck)



$$Z = \frac{\sigma S^2}{\kappa}$$

Construction of a typical commercial device

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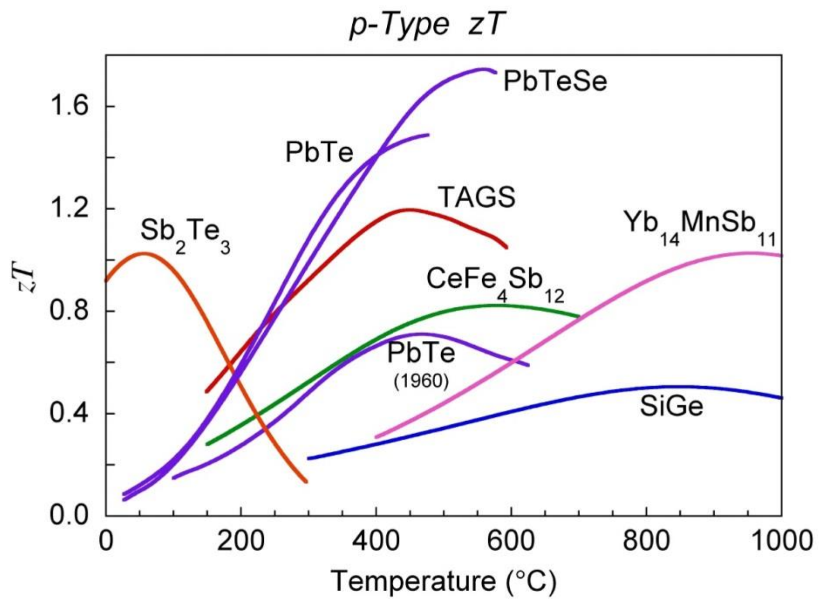
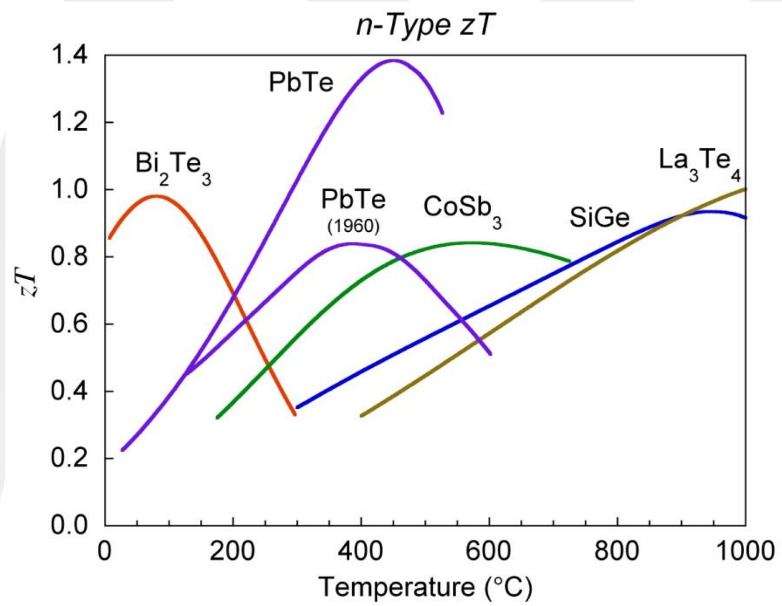
TYPICAL THERMOELECTRIC SEMICONDUCTORS





- No material covers wide temperature range
- Average ZT is not far from 1
- Dependence on low abundance materials

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MATERIAL LEVEL EFFICIENCY

A simplified expression which relates the Carnot efficiency and TE material figure of merit at optimum efficiency:

$$\eta = \frac{\Delta T}{T_h} \frac{(M-1)}{(M + \frac{T_c}{T_h})}$$

$$Where\ M = (1 + ZT_{avg})^{1/2}$$

$$Z = \frac{\sigma S^2}{\kappa}$$

Example:

T_h = 500⁰C

T_c = 100⁰C

ZT_{avg} = 0.6

η = 7.8%

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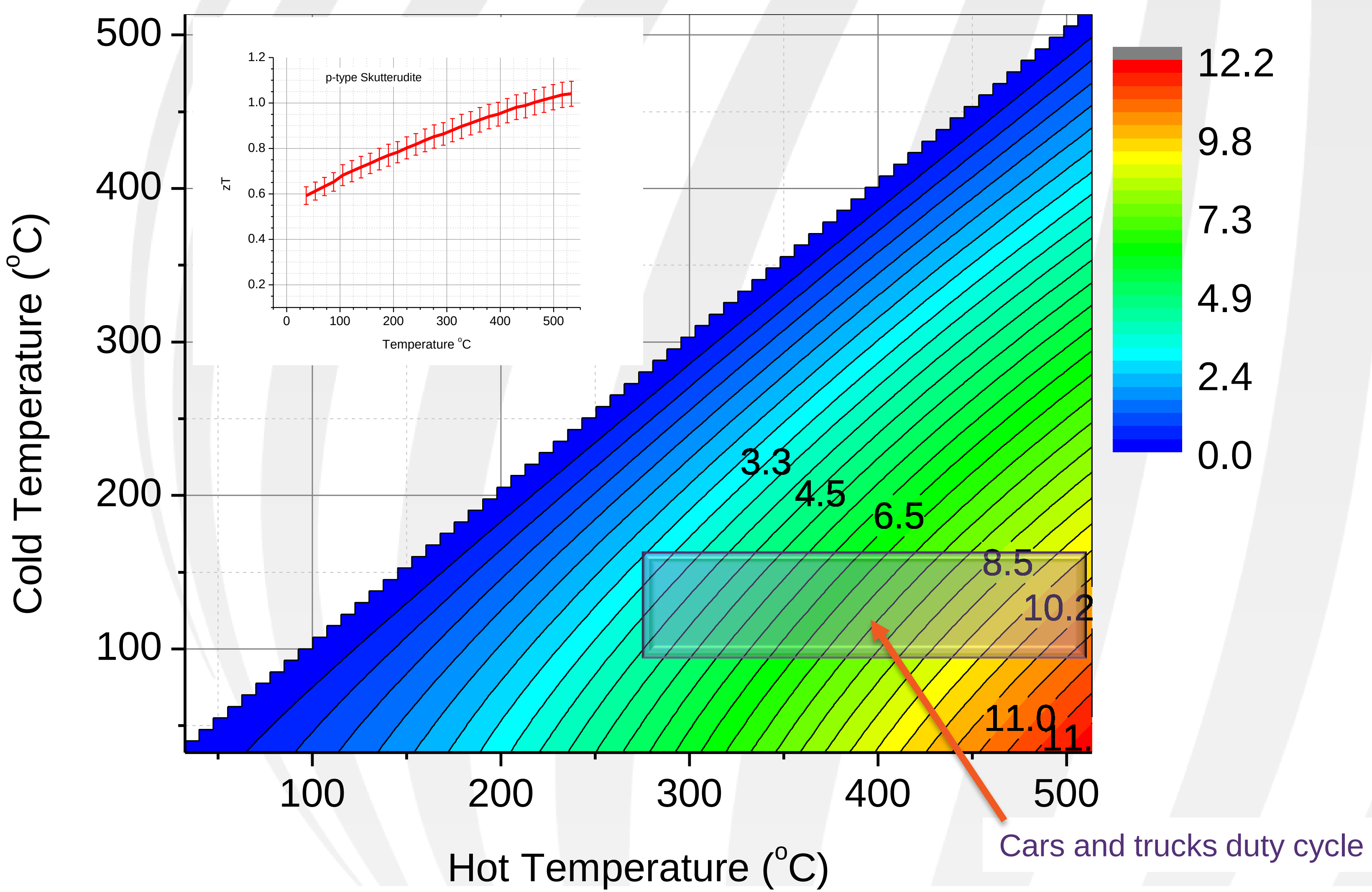
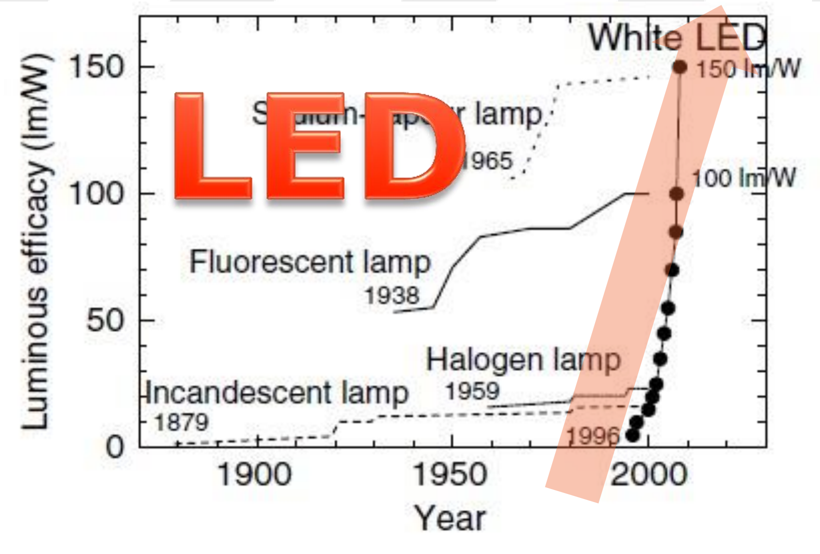
Theoretical Efficiency of a Couple

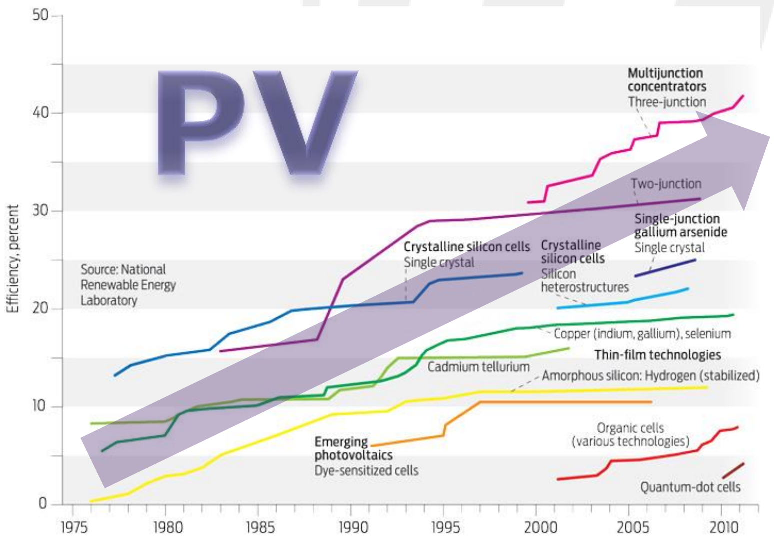


Assumption: no parasitic losses.

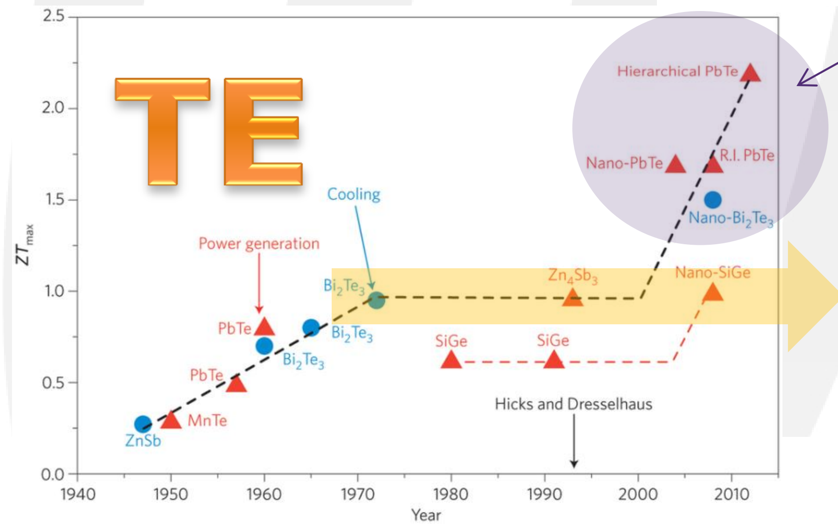
PROGRESS IN TE MATERIALS

Painfully slow, compared to other solid state technologies





Academic publications, not reduced to practice



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DEVICES

CTE mismatch of layers

High thermal gradients

Brittleness of TE materials

Parasitic electric losses

Oxidation and sublimation

CHALLENGES:

Thermal

Electrical

Mechanical

Chemical

Parasitic thermal losses

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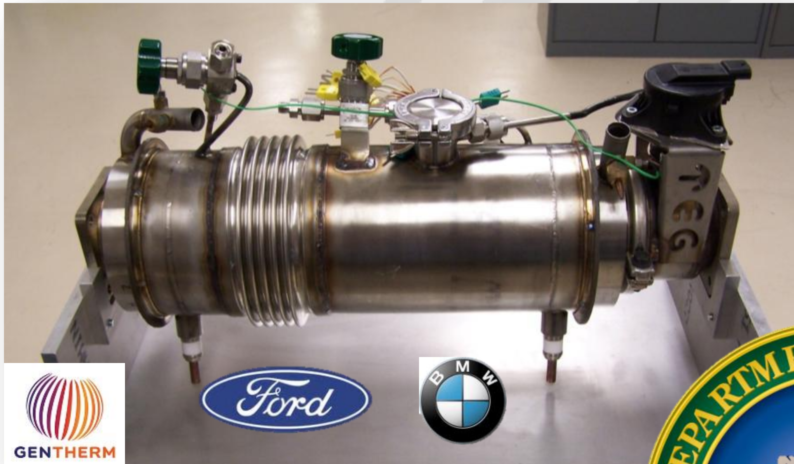
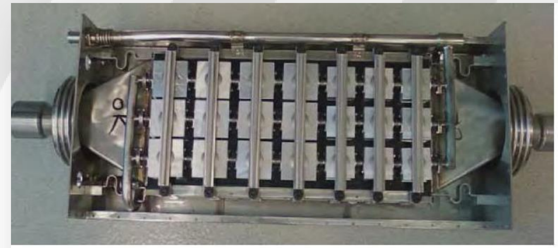
APPLICATIONS AND ECONOMICS

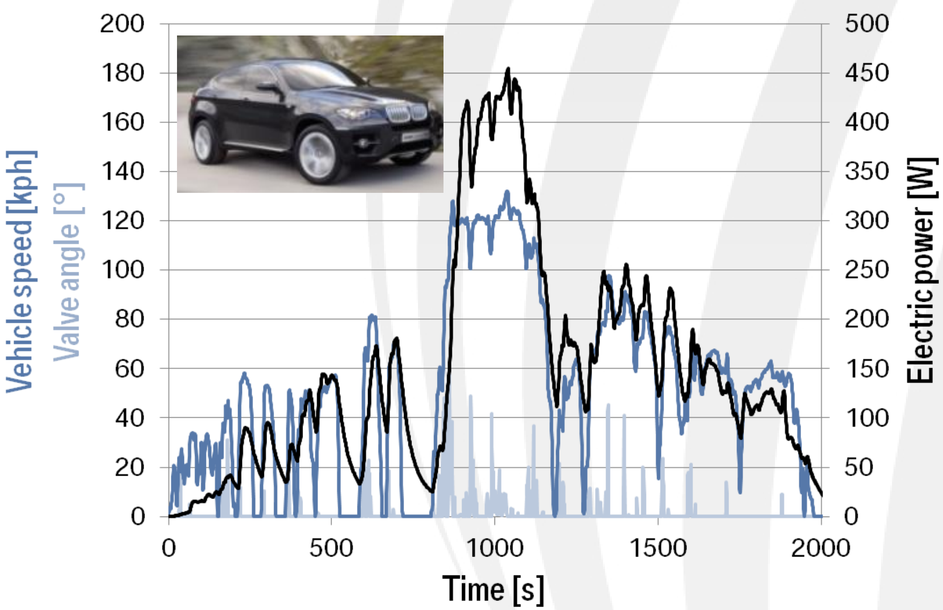
DOE-SPONSORED WORK SINCE 2005

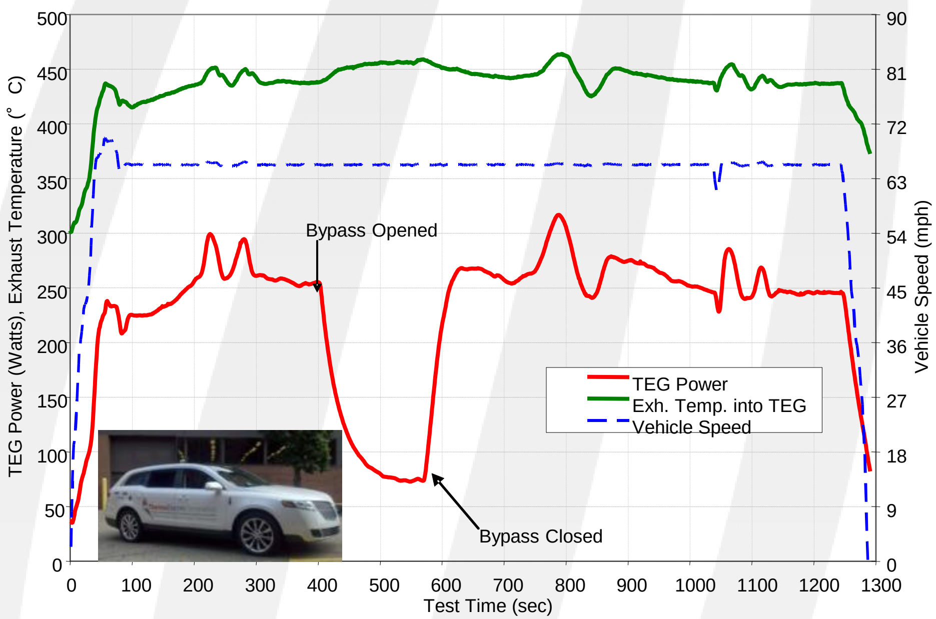




- 10,000 km on the road
- Up to 600 W at 130 kph

REAL-LIFE DRIVING: BMW X6 AND LINCOLN MKT





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DEVICES – TOWARDS VOLUME MARKETS

- Tight integration with heat exchangers
- Hot side – 500-650 C
- Cold side – 20-100 C, water cooled
- System efficiency – 1-3%, depending on conditions
- Amount of power generated – 20-40W per cartridge

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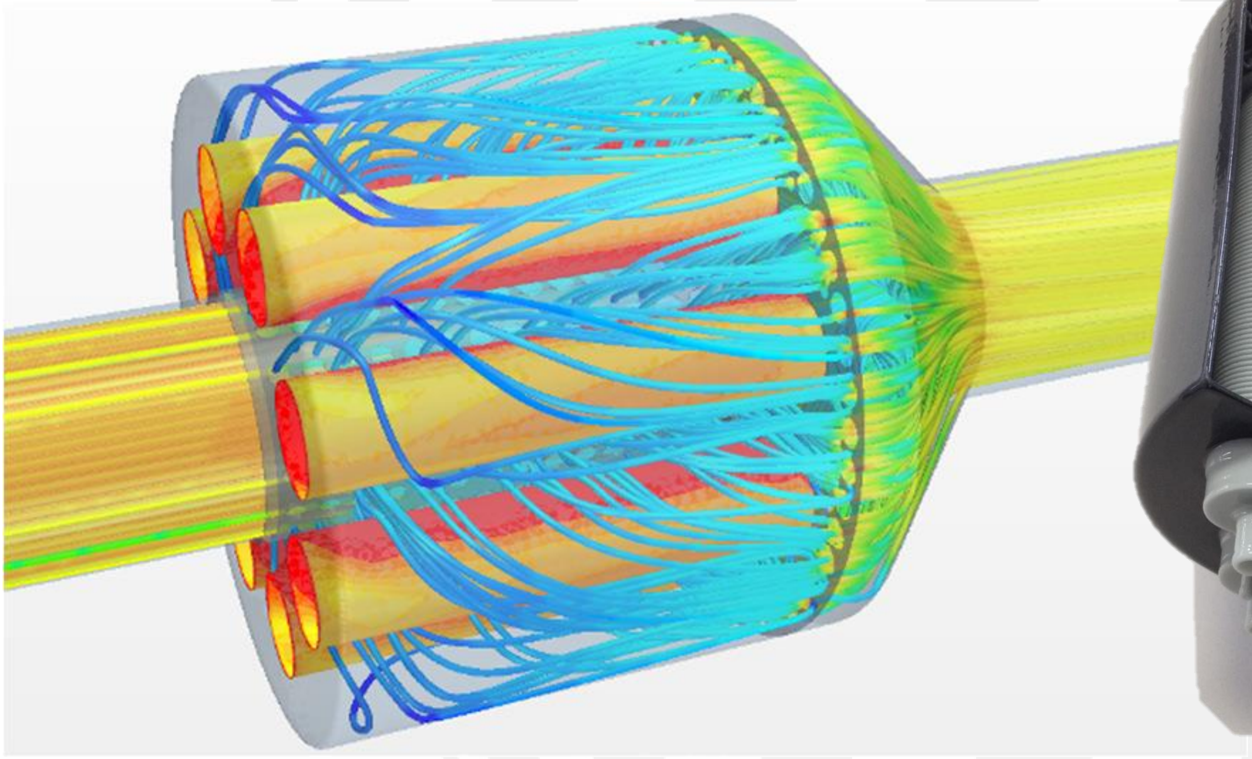
EXAMPLE OF APPLICATION INTEGRATION – AUTOMOTIVE EXHAUST



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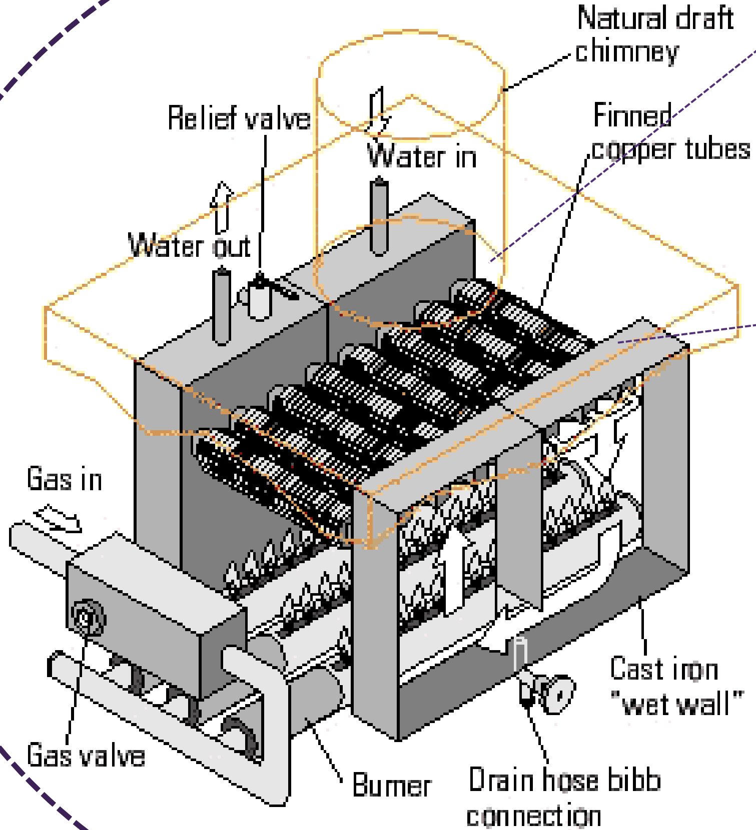
EXAMPLE OF APPLICATION INTEGRATION - BURNERS

Non-condensing residential boiler



10-300 W to power:
- Controls?
- Communications?
- Pumps?
- Blowers?

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ECONOMICS – THE CURSE OF $1/W

- A metric of $1/W is often cited as economic goal
- Why is it not always appropriate?
  - Ambiguity of boundary conditions definition ($1/W for materials? Devices? Systems?)
  - Lacks definition of application specific duty cycle (Watts of peak power? Average over regulatory cycle? Customer cycle?)

Between $30 and 200/W
Sold in millions

~$60/W
Sold in thousands

The real economic question is: what is the value of electricity in particular application??

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VOLUME ECONOMICS

- Top-down: driven by fuel efficiency in mobility applications, few % FEI
  - Passenger cars
  - Long-haul trucks
  - Fleets

- Bottoms-up challenges
  - Supply chain does not exist
  - Materials are not scaled up

Economics is explored in the current DOE EERE program

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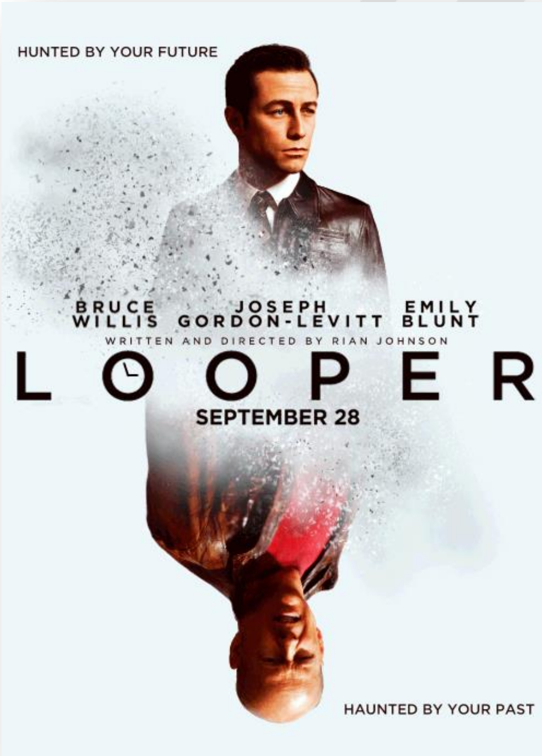
MASS CULTURE VIEW OF WASTE HEAT RECOVERY



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