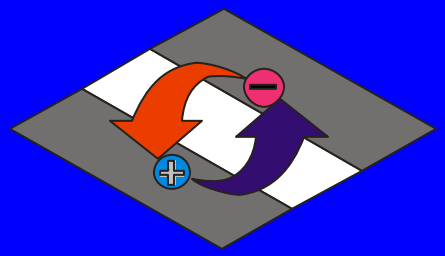
Developments in Thermoelectric Power Generation



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School of Engineering, Cardiff University

1. Thermoelectric Effects

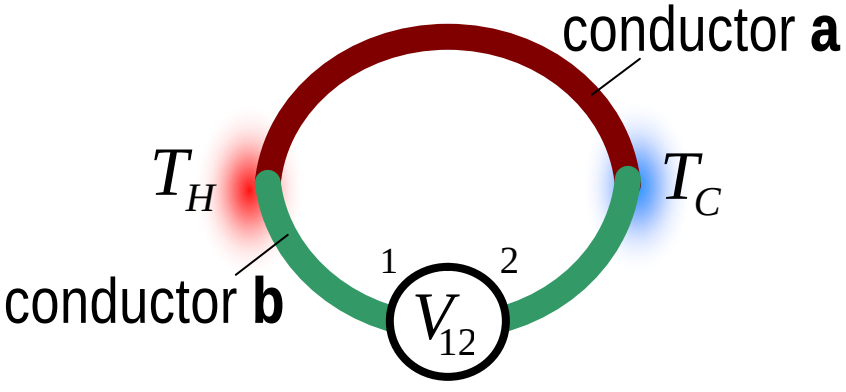
2. TE Power Generation

3. Typical Applications

4. Future Prospects

THERMOELECTRIC EFFECTS

Seebeck effect

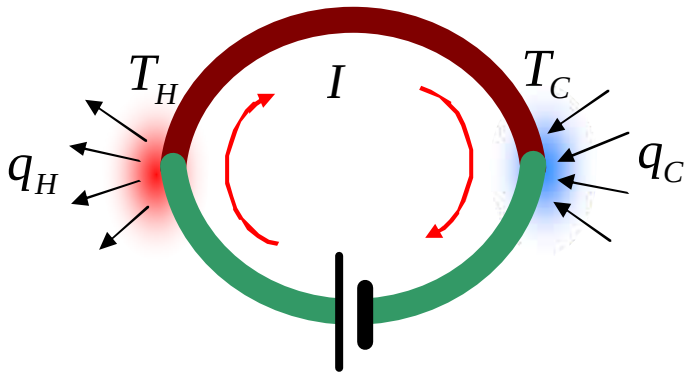


$$V_{12} = a_{ab}(T_H - T_C)$$

Generation

α – the Seebeck coefficient

Peltier effect



$$q = p_{ab} I$$

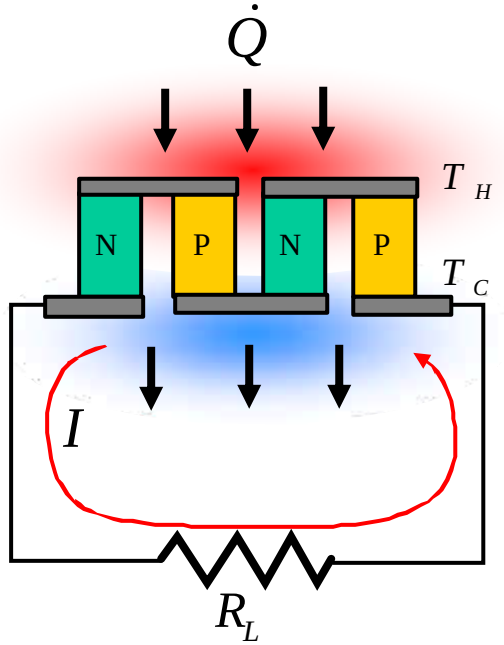
Refrigeration

π – the Peltier coefficient

POWER GENERATION

Power Output:

$$P_{\max} = N \cdot \frac{a^2 (T_H - T_C)^2}{4R}$$



Conversion Efficiency:

$$h = \frac{\text{Power delivered to the load } (P)}{\text{Heat absorbed at the hot end } (\dot{Q})}$$

$$h_{\max} = \left(\frac{T_H - T_C}{T_H} \right) \left[\frac{(1+ZT)^{1/2} - 1}{(1+ZT)^{1/2} + T_C/T_H} \right]$$

Carnot efficiency

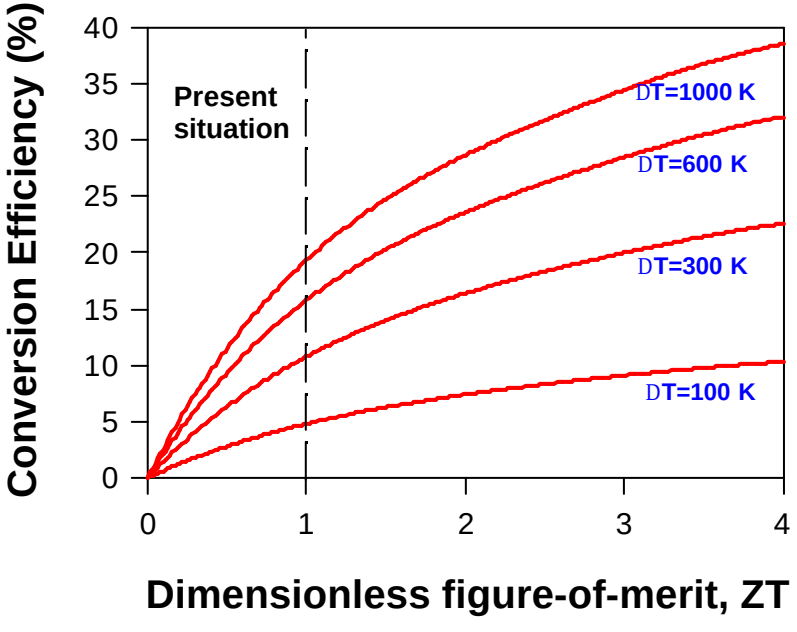
Material properties

$$ZT = \frac{a^2 T}{RK}$$

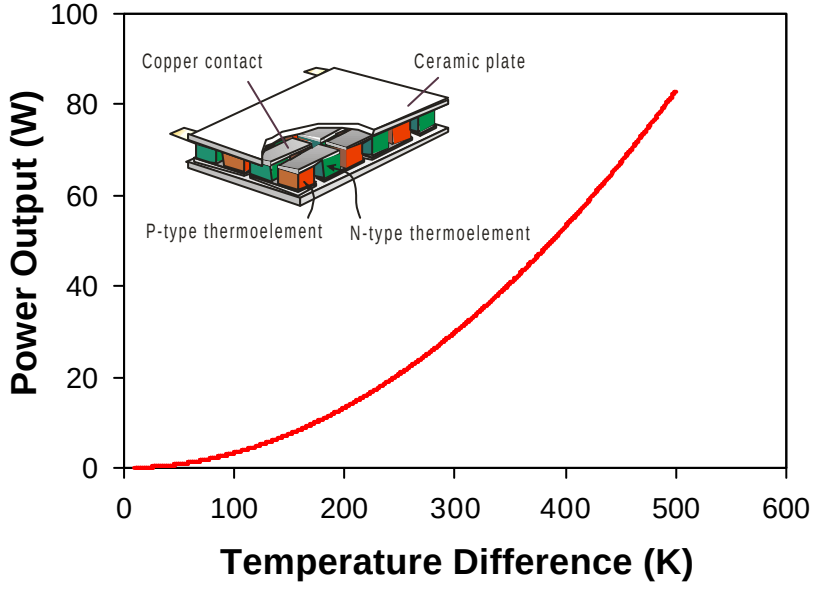
Thermoelectric Figure-of-merit

POWER GENERATION PERFORMANCE

CONVERSTION EFFICIENCY

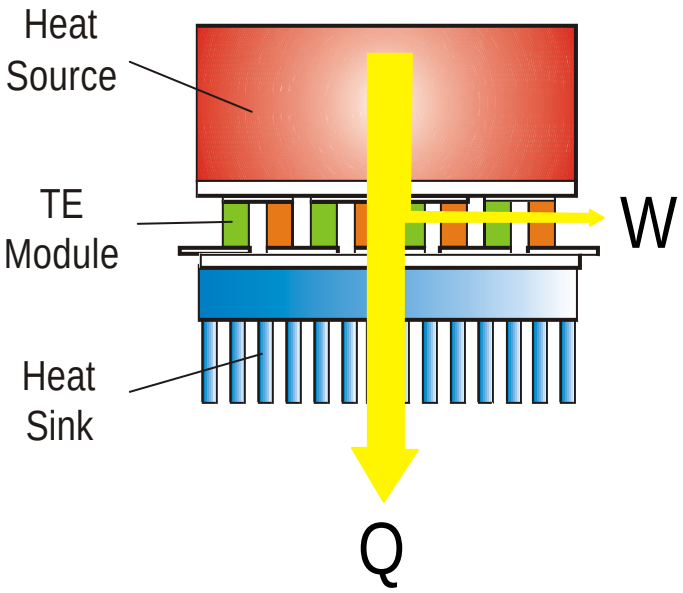


POWER OUTPUT

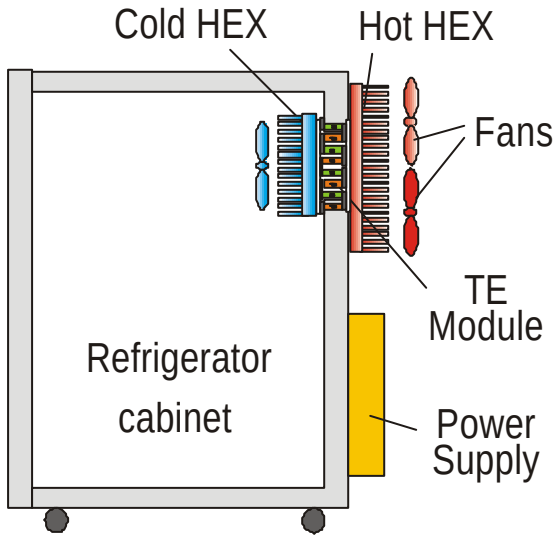


THERMOELECTRIC SYSTEMS

Generation



Refrigeration



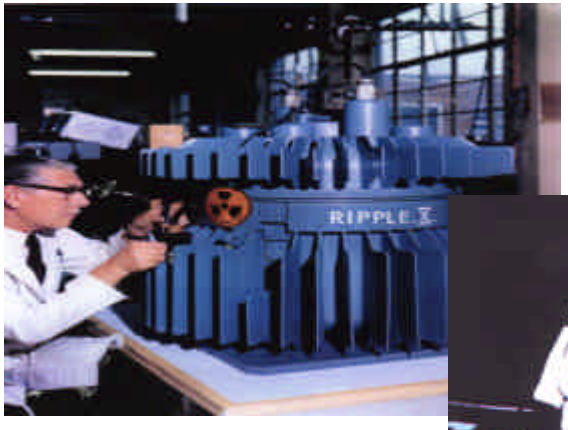
Advantages:

- No harmful working fluids - environmentally friendly
- No moving parts – reliable and no noise
- Wide power range – totally scalable from μW to MW

Disadvantages:

- Relatively low efficiency

Radioisotope Thermoelectric Generator for Space



Power Output: 280 W

L: 1.1 m D: 0.4 m

Half life: 87 years

Pu-238 SiGe

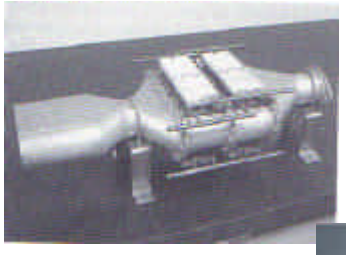
GPHS-RTG

Pioneer (1972, 42W)
Voyager (1976, 156W)
Galileo (1989, 290W)
Cassini (2002)
New Horizon (2006, 280W)

Bellona (~80W, 136 for Russian lighthouses, Sr - 29 years)

No any other alternative

Thermoelectric Generation from Waste Heat



US FreedomCar Program: 4 thermoelectric consortium:

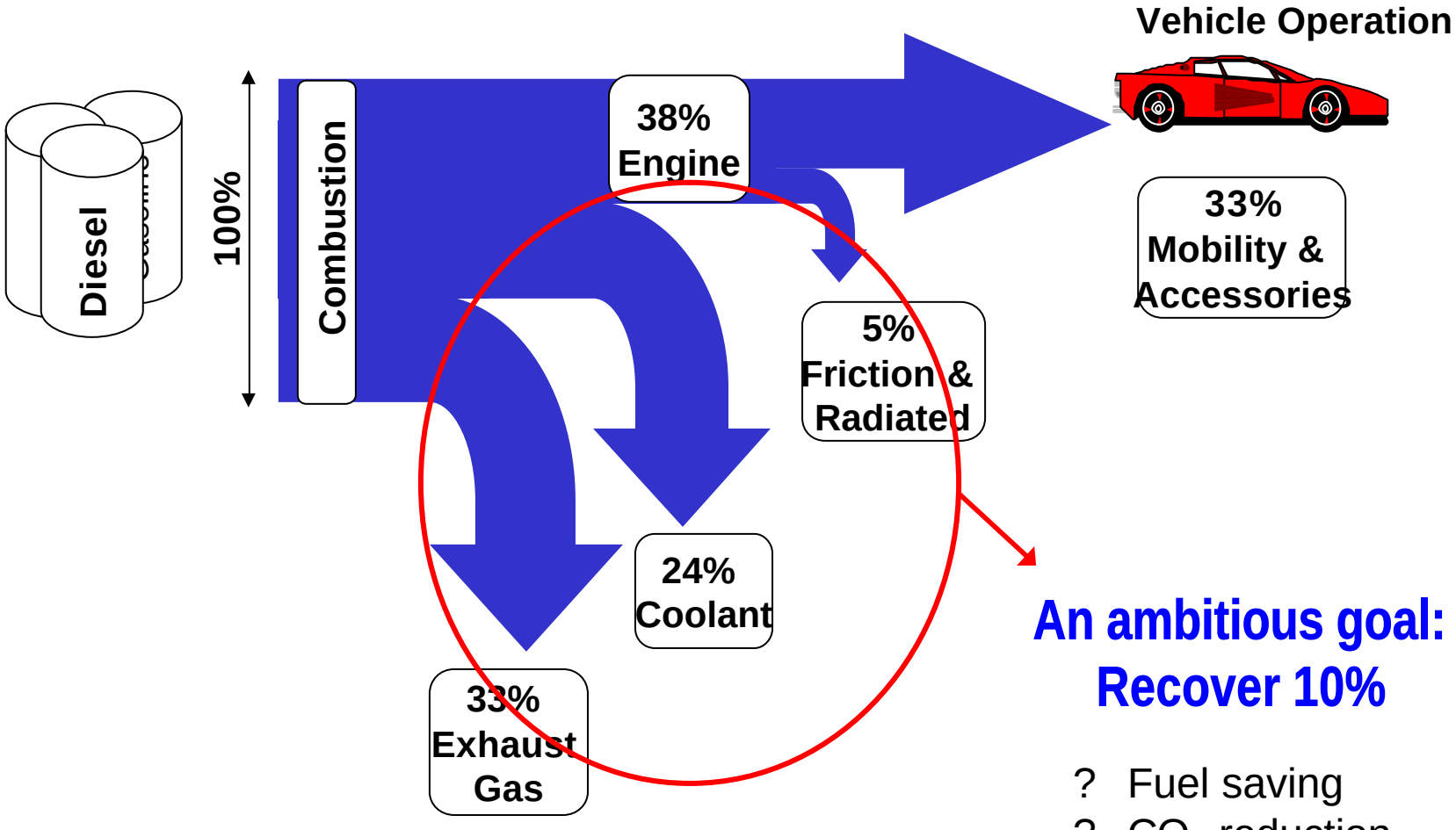
- *BSST* with ***BMW***, Visteon, Marlow, Virginia Tech, Purdue, UC-Santa Cruz
- ***GM*** with GE, U of Michigan, U of South Florida, ORNL, RTI
- Michigan State with Cummins, Tellurex, ***NASA-JPL***, Iowa State
- United Technologies with ***Pratt & Whitney***, Hi-Z, Pacific Northwest National Lab., and Caterpillar

Japanese National Thermoelectric Project:

- IHI
- Komatsu
- Toshiba
- UBE Industries
- Yamaha

Hot Water Generator (100W, 3.5%)
Cardiff University

Heat Distribution in Vehicles



An ambitious goal:
Recover 10%

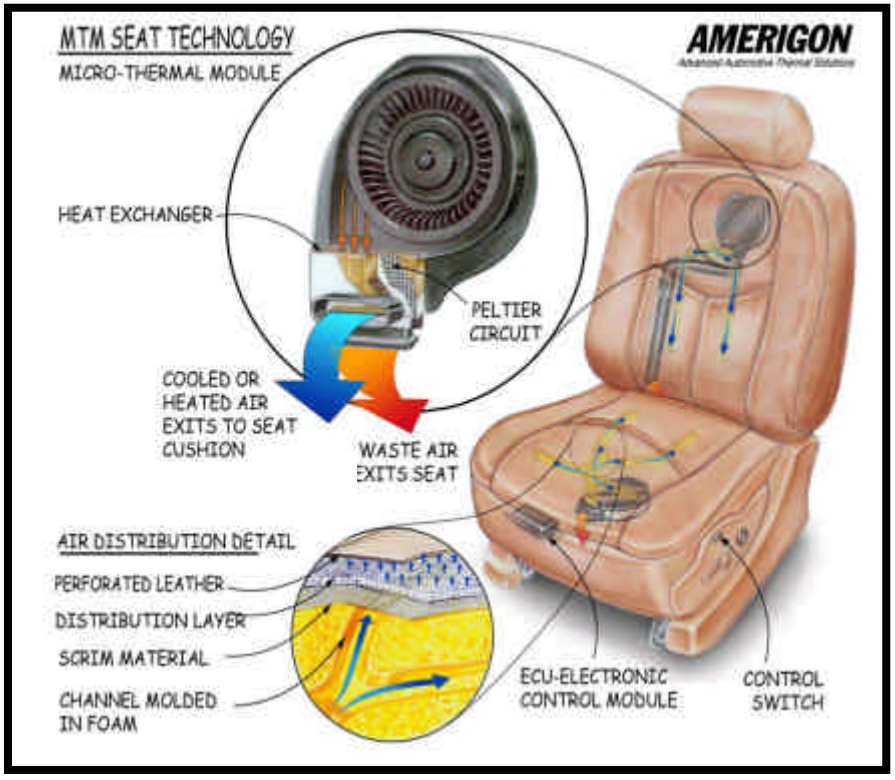
? Fuel saving
? CO_2 reduction

Thermoelectric Cooling Applications

Competitive for small volume cooling

Picnic coolbox

Cooling laser



Amerigon: Climate Control Seat™ (CCS™)

Distributed Cooling/Heating: Eliminate R-134a refrigerant

World market:US$200-250M/yr

TE Power Generation Using Flame

500 W TEG, natural gas pipeline, Peru
[LeSage, Global Thermoelectric]

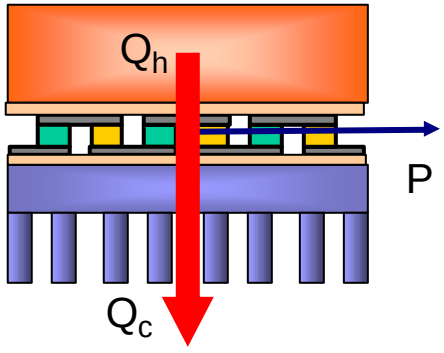
Niche market for TE power generation (US$25-50M/yr)

Used in remote area where frequent maintenance is not impossible, such as:

- Oil or gas pipelines
- Well sites
- Offshore platforms
- Telecommunications sites
- Cathodic protection
- Well automation
- Monitoring equipment
- Navigational aids
- Communications systems

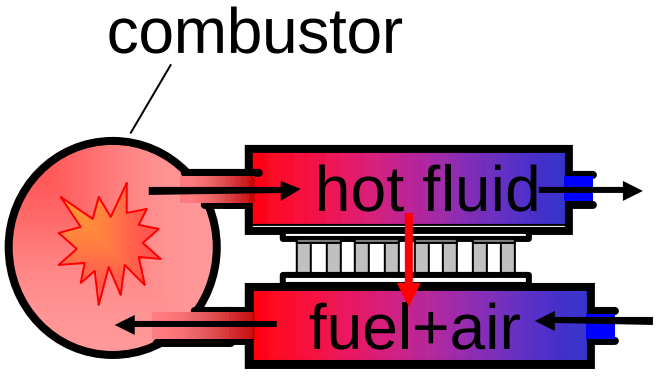
Natural gas: 48 m^3/day
Propane: 76 litre/day
Ethylene: 30 m^3/day
Diesel:

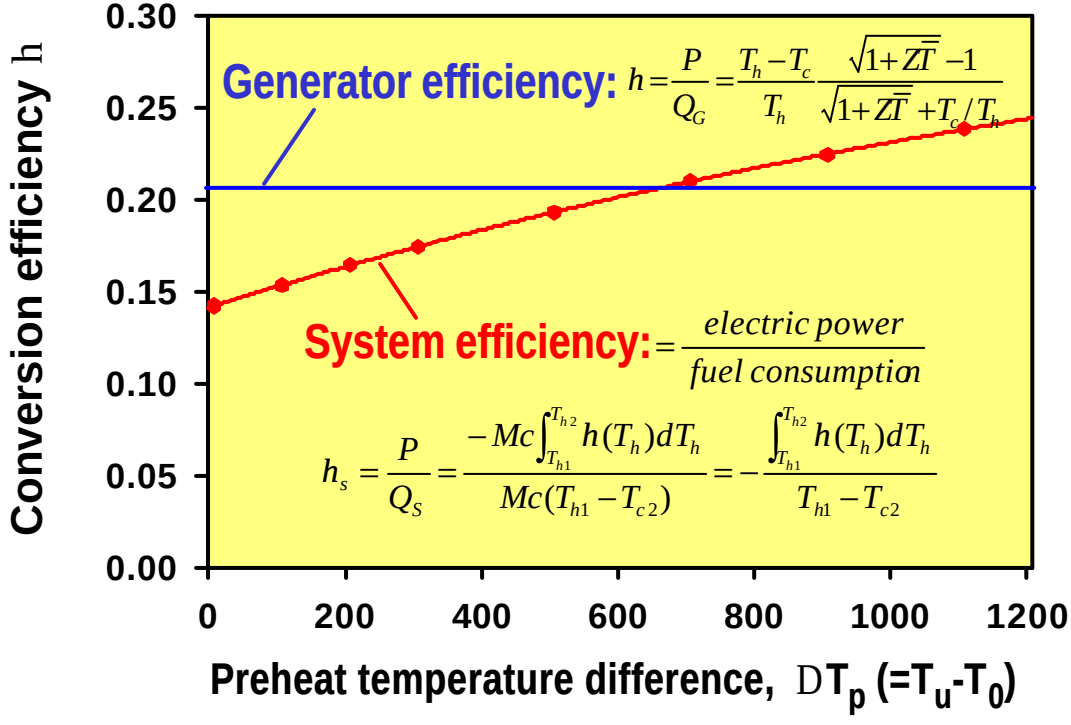
Thermoelectric Regenerative Combustion



A lot of waste!
Make use of it?

Advantages:
- Improved conversion efficiency
- Lean-fuel combustion
- Heat and power co-generation





Philips Research – Woodstove

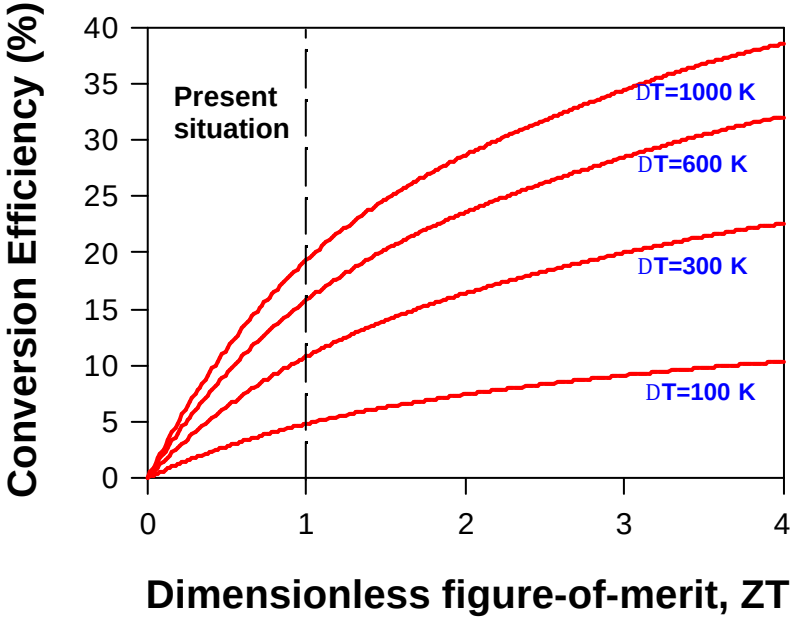
Stove with self-powered fan using thermoelectric generator

- Philips Research Eindhoven, The Netherlands (Paul van der Sluis)
- 400 million stoves world wide market
- Pilot of 1000 pieces in India
- TEG powers fan to regulate combustion and charge the ignition battery

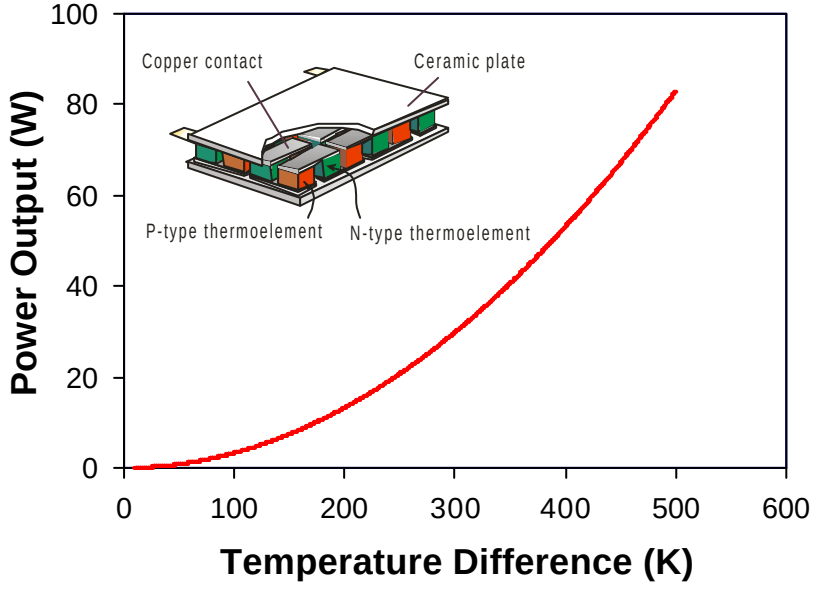
Benefits:
- Burn more efficiently
- Regulated combustion
- Reduce smoke and toxic emission

POWER GENERATION PERFORMANCE

CONVERSTION EFFICIENCY



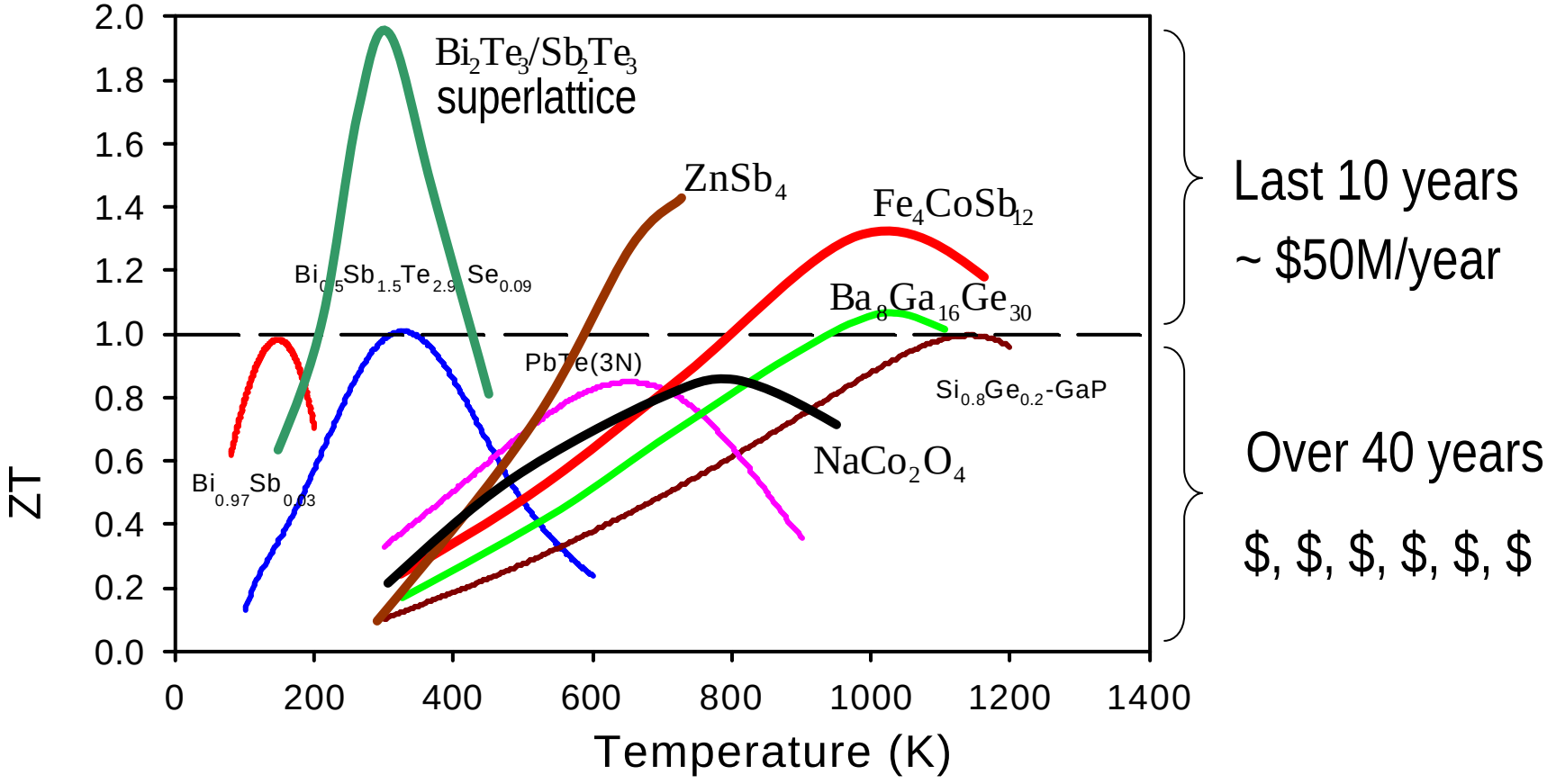
POWER OUTPUT



$$ZT = \frac{a^2 T}{RK}$$

Thermoelectric figure-of-merit

Materials with Large ZT



Is it worth of the efforts?

Past, Present and Future

1940-1960	1960-1990	1990-2007	Future
ZT ~ 0.6	ZT ~ 1.0	ZT ~ 1.5	ZT > 4?
The birth of useful TE devices with limited military and space applications.	The launch of TE industries with a steady growth and a niche market.	Steady growth of TE markets. Resurging of interests in TE research.	Breakthrough will lead to a revolution in the renewable energy field.

Two Exciting Predictions in 1950s

Discovery of Semiconductors

Well-known

Vacuum Valves replaced by solid-state transistors

↓

Invention of silicon based integrated circuits

↓

Information technology revolution

Reality!

Less well-known

ZT > 4

↓

Turbine engines or compressors to be replaced by thermoelectric converters

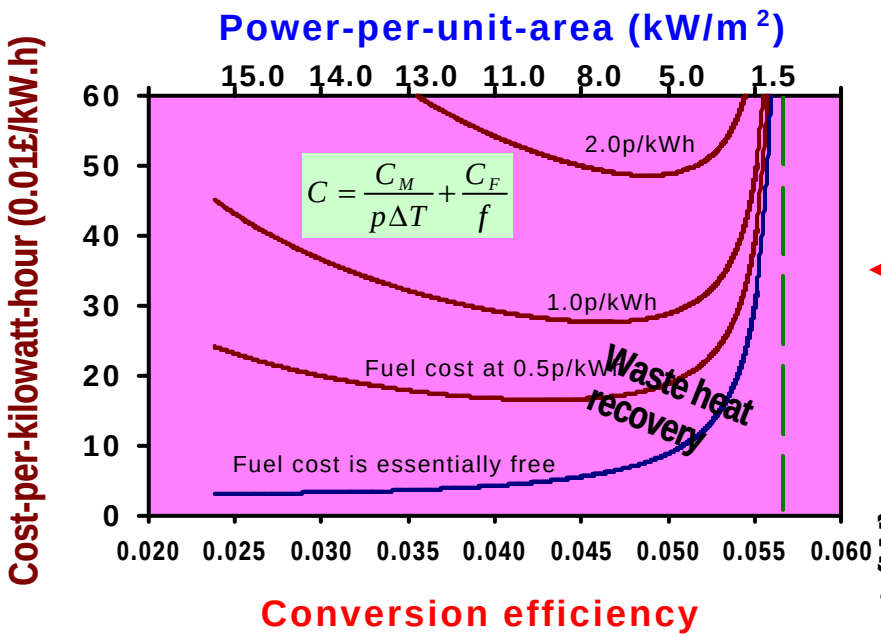
↓

Energy technology revolution Save the planet

Dream?

Thank You

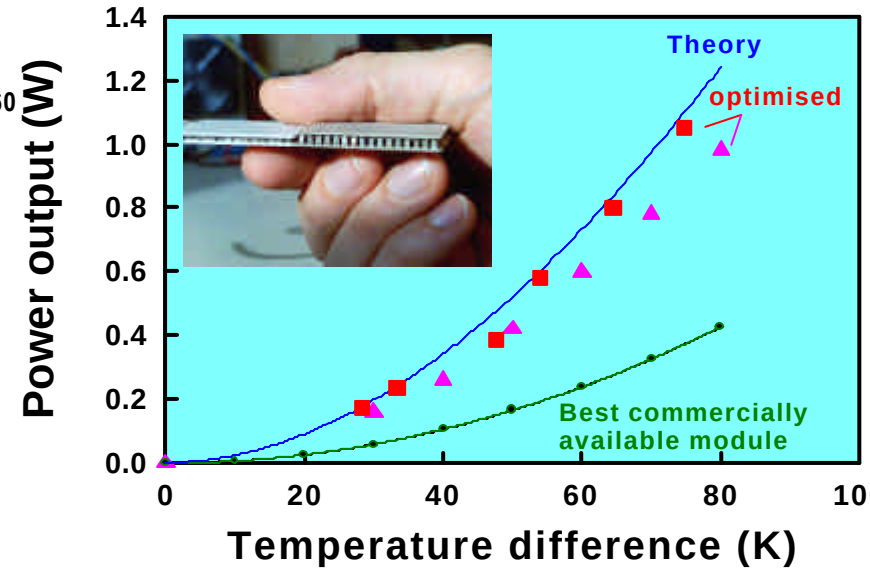
Module Design for Waste Heat Recovery



Suitable for waste heat recovery

Increasing the power output will lead to reduce the cost of power per module

The power output can be increased by reducing the length of thermoelements.



Ref. Gao Min and Rowe, 2002, Energy Conversion & Management (43) 221-228

THERMOELECTRIC APPLICATIONS

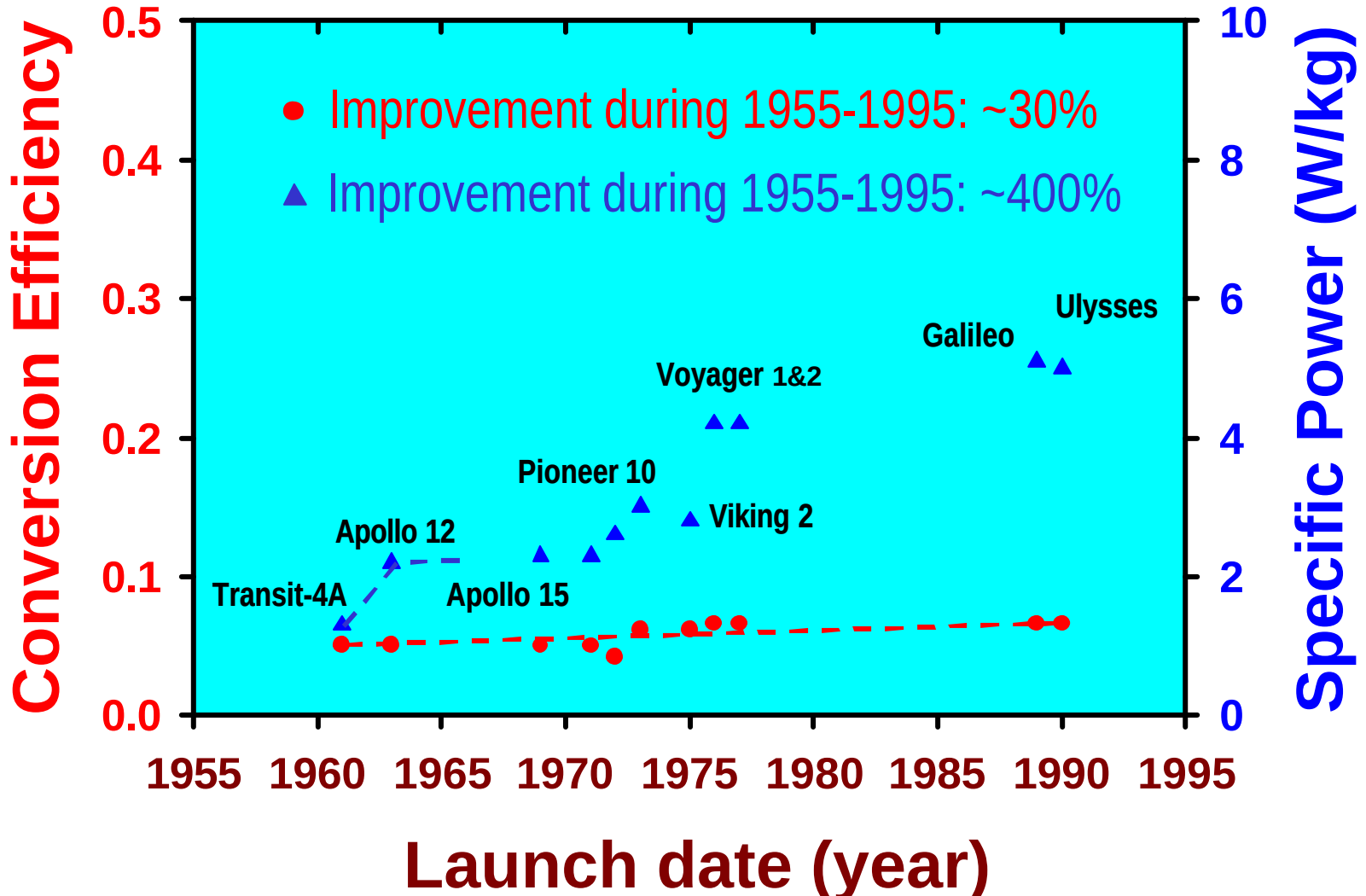
Advantages:
- Environmentally friendly
- No moving parts – reliable and no noise
- Wide power range – From μW to kW

Disadvantages: Relatively low efficiency

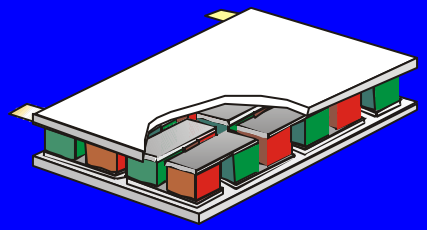
Generations:
- Space power – long period,unattended power source
- Waste heat recovery:
  - Industrial waste heat
  - Geothermal
  - Vehicle exhaust
  - Body heat

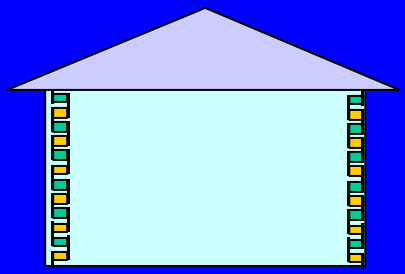
Refrigeration:
- Electronic components:
  - Infra-red detectors
  - Laser diodes
  - Computer chips
  - Photomultipler
- Low-temperature cabinet:
  - Mobile picnic box
  - Dehummiditifier
  - Constant T bath
  - Dew point dectector

Engineering v.s. Science

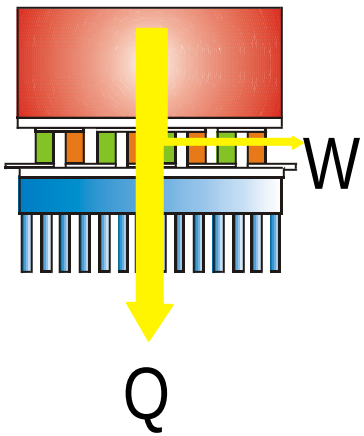


Thermoelectric Energy Conversion – A Great Concept !

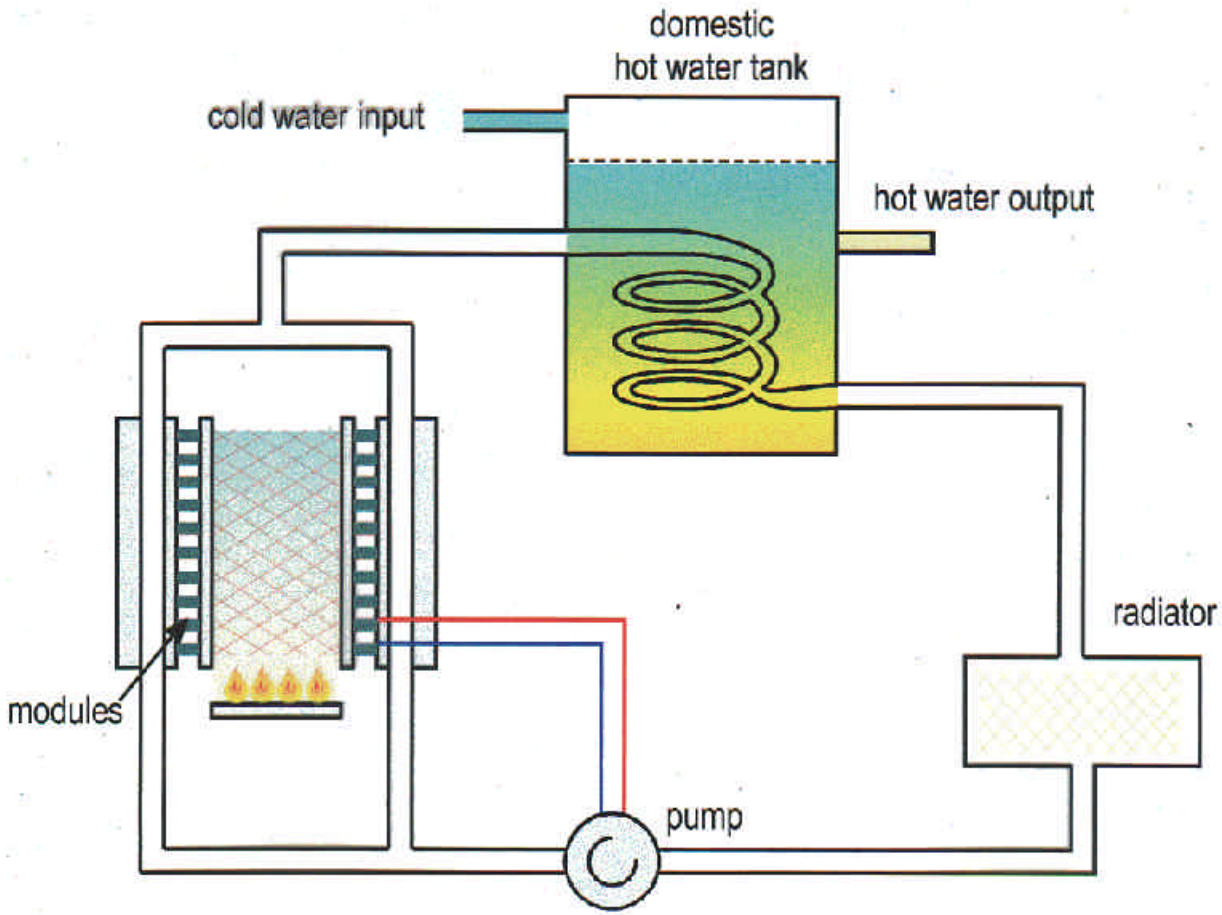




"Symbiotic" Applications: Central Heating System

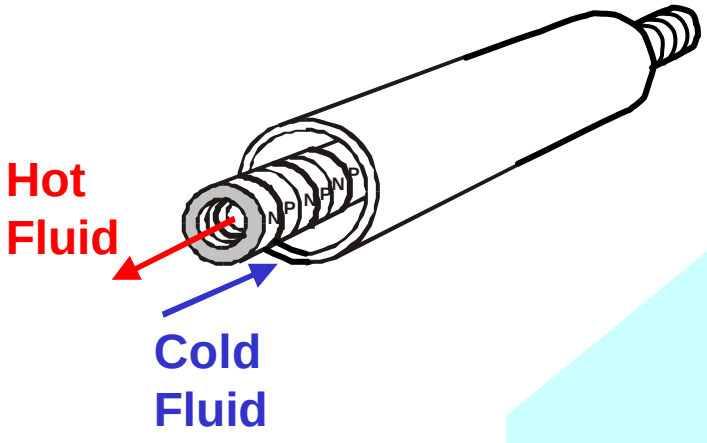


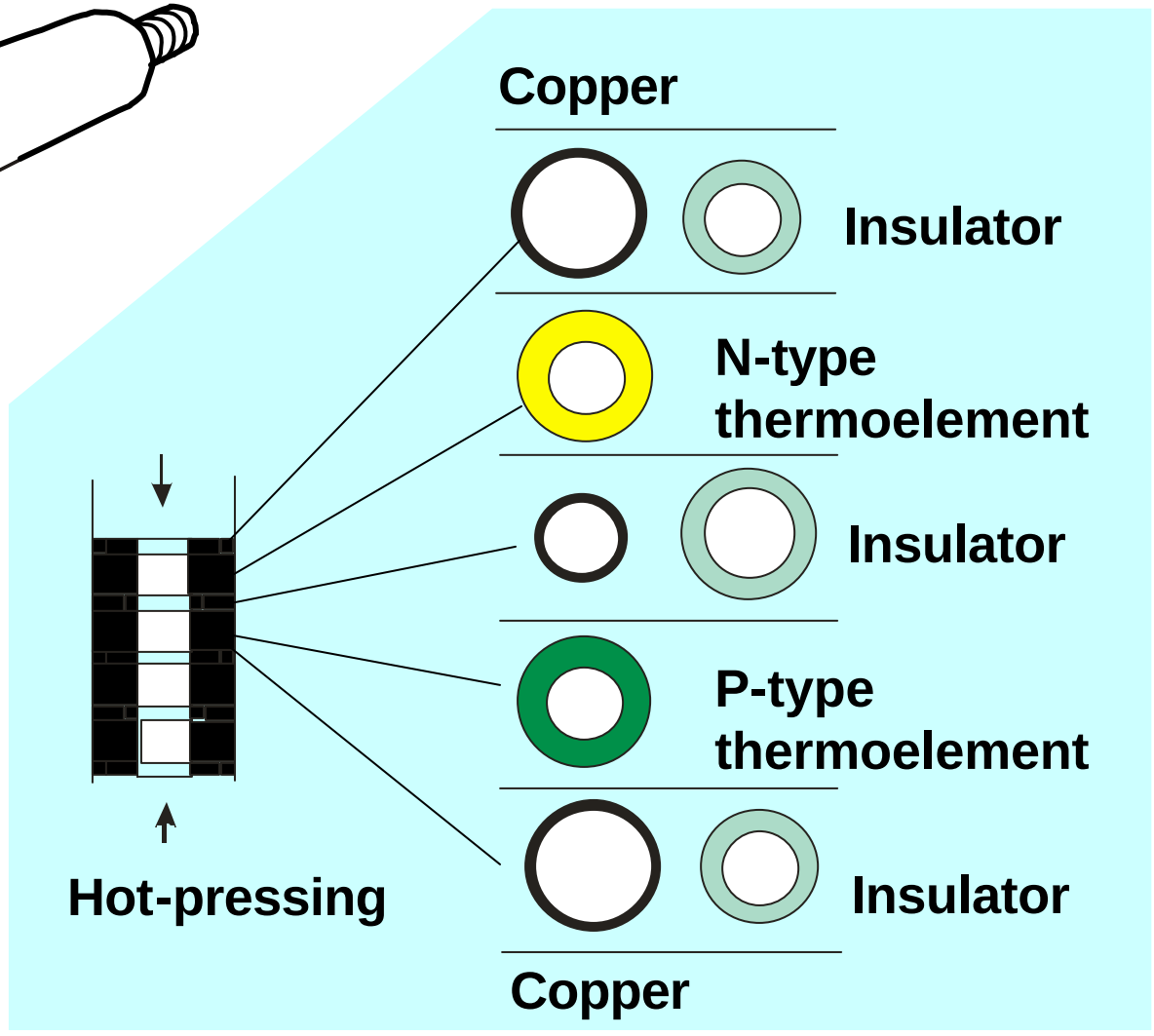
Making Q useful by heating the water!



Ref: Gao Min and D.M. Rowe, *Energy Conversion and Management,* 43 (2002) 221-228

Ring-Structured Thermoelectric Module





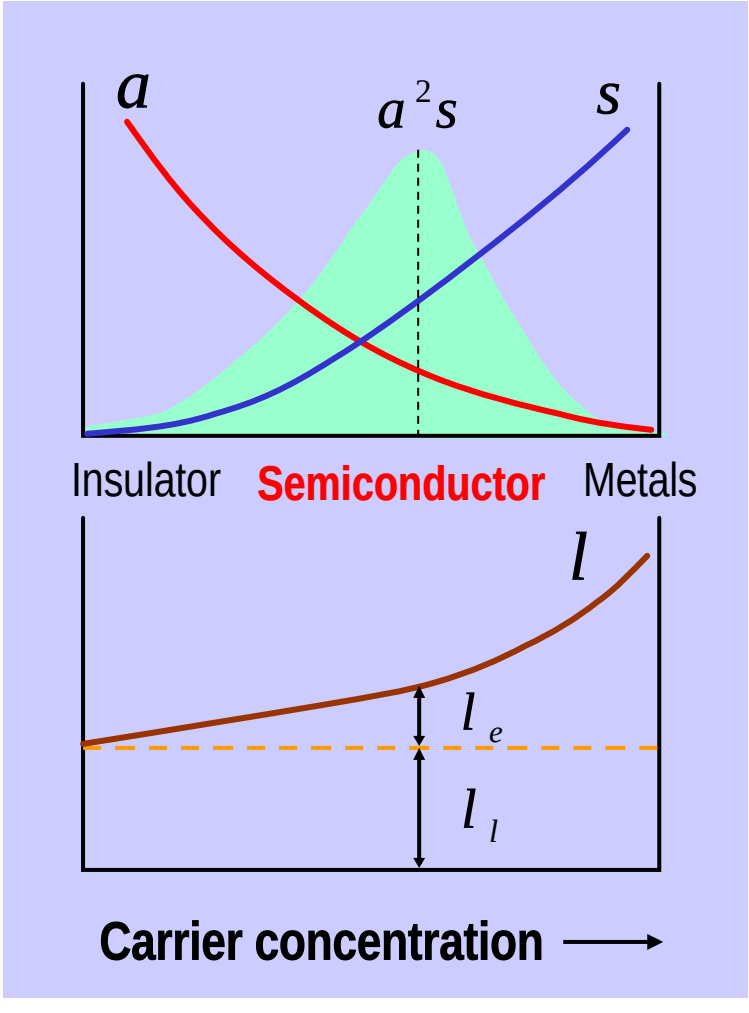
Thermoelectric Figure-of-Merit, ZT

Seebeck coefficient

Electrical conductivity

$$ZT = \frac{a^2 s\, T}{l}$$

Thermal conductivity



The Seebeck effect was discovered in 1821. However, practical thermoelectric materials were only developed more than 100 years after its discovery.

Thermoelectric Power Generation using Body Heat

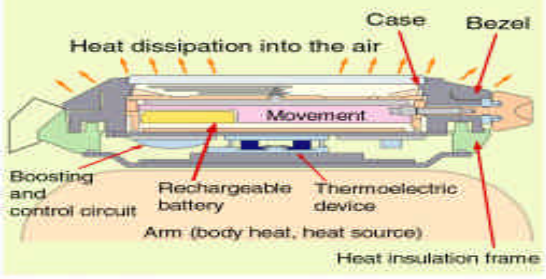
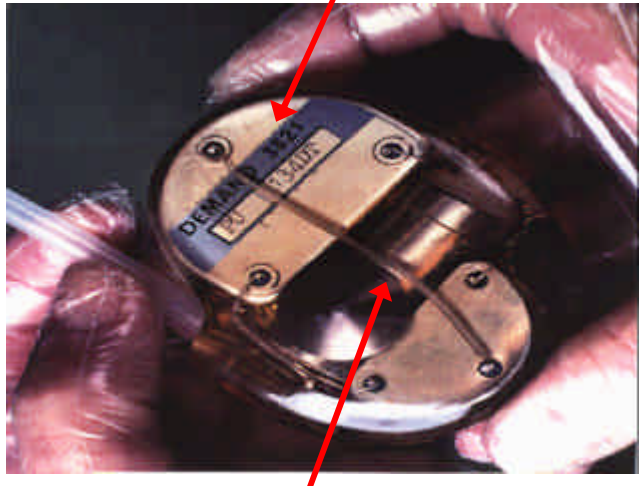


Fig. 5: The conceptual figure of the thermoelectric-powered wristwatch
The back lid (high-temperature end) receives heat from the wearer's arm effectively while the clock case (low-temperature end) radiates heat efficiently.

Seiko (45㎽), Citizen (14㎽)

Cardiac Pacemaker

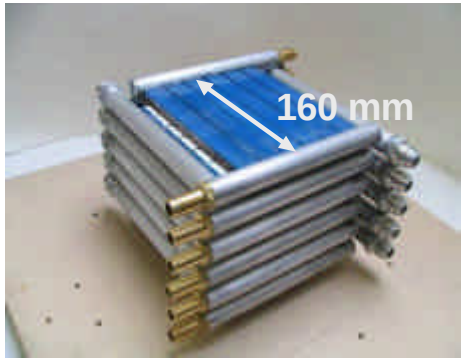


Miniature RTG battery

- Power output: ~ 30 μW
- Life-time: > 20 years

US DoE FreedomCar Thermoelectric/Vehicle Programs

- Thermoelectric Generator Teams
  - *BSST* with ***BMW***, Visteon, Marlow, Virginia Tech, Purdue, UC-Santa Cruz
  - ***GM*** with GE, U of Michigan, U of South Florida, ORNL, RTI
  - Michigan State with Cummins, Tellurex, ***NASA-JPL***, Iowa State
  - United Technologies with ***Pratt & Whitney***, Hi-Z, Pacific Northwest National Lab., and Caterpillar
- Nano/high ZT materials not yet available
- Barriers to entry
  - Cost
  - Heat transfer to/from TEG
  - Weight
  - Acceptance of change
  - Competition
    - Honda / Rankine (+3.8%)
    - BMW / Turbosteamer (15%)



500 Watt BiTe TEG [BSST]

1 kW TEG on a Kenworth Truck [Hi-

BMW 530i Concept with TE Generator (yellow) [BMW]

The most promising TE greentech application: vehicle waste heat