Thermoelectricity Engineering (modules, performance, applications)

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Ecole thématique du CNRS
Organisée par le GIS «Thermoélectricité»
Approches pluridisciplinaires de la thermoélectricité : bases, théorie, matériaux et applications
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Thermoelectricity
Engineering (modules, performance, applications)

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Presentation

Applications of Thermoelectricity

•1. Introduction

Description of the elements of a thermoelectric generator.
Concept of thermal
Power and Efficiency of thermoelectric generators.
Modules marketed or in the process of being marketed.

•2. Design of thermoelectric generators

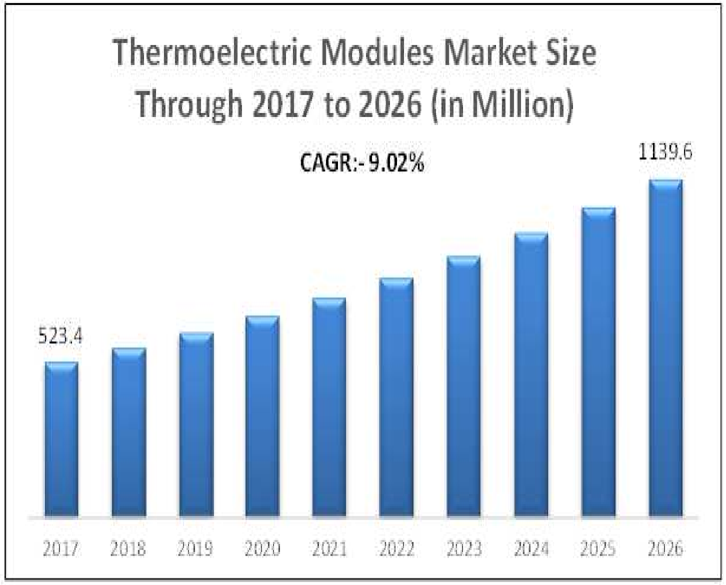
Modeling of thermoelectric modules
Complete generator model (from heat sources to electrical storage including electrical converters)
Design and optimization
Study of an example and practical aspects

•3. Applications

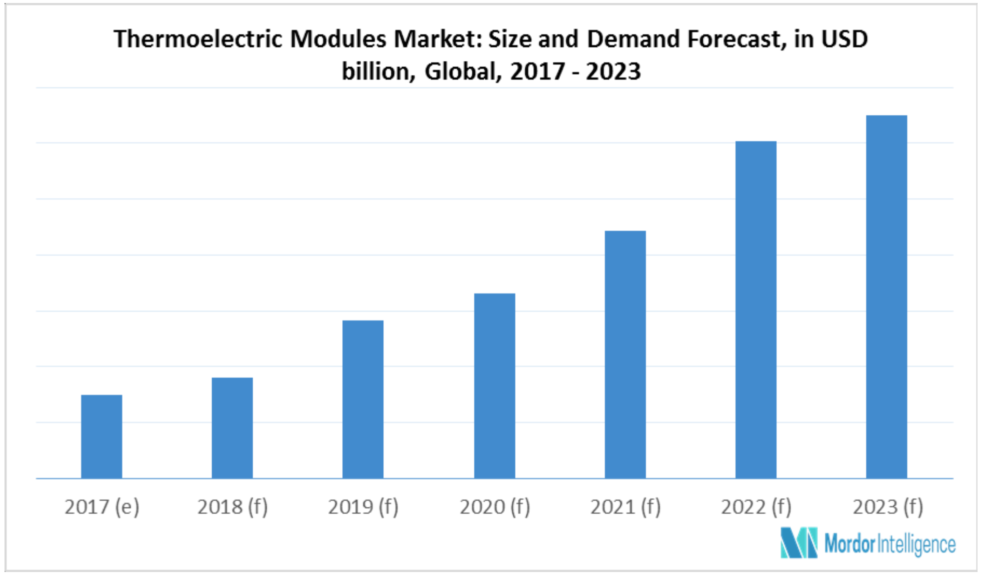
Production in extreme environments
Waste Heat Recovery (WHR)
Domestic production
Microgeneration: sensors, connected objects (IOT)
Thermoelectric solar power
Cooling
Metrology

Thermoelectricity

Market from market research companies



Source: Maximize Market Research

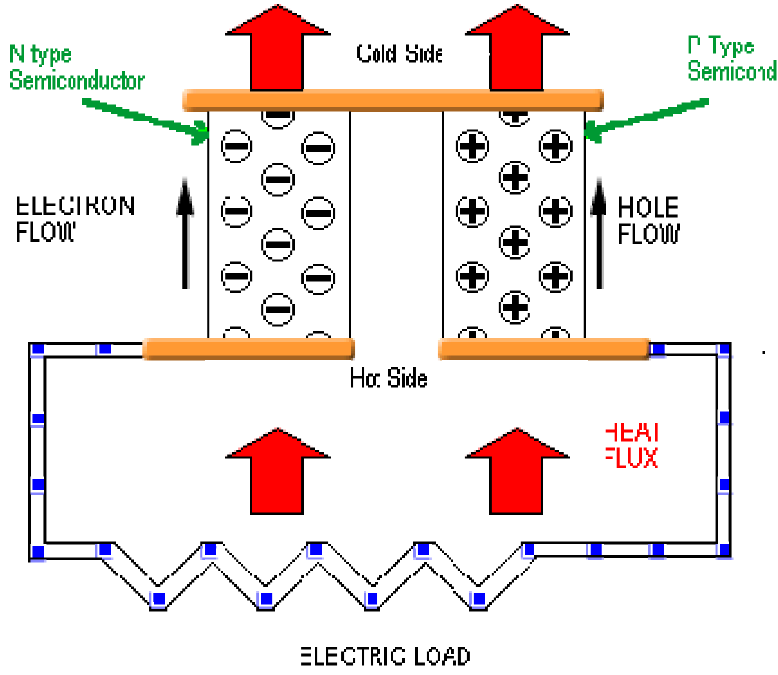


Let's be optimistic

elements of a thermoelectric generator

One couple of a seebeck module

consists of one N-Type and one P-type semiconductor pellet



- **figure of merit** $$Z = \frac{\sigma.\alpha^2}{\lambda}$$

σ is the electrical conductivity

λ is the thermal conductivity

- **dimensionless figure of merit ZT**

$$ZT = \frac{\sigma.\alpha^2.T}{\lambda} \qquad T = \frac{T_h + T_c}{2}$$

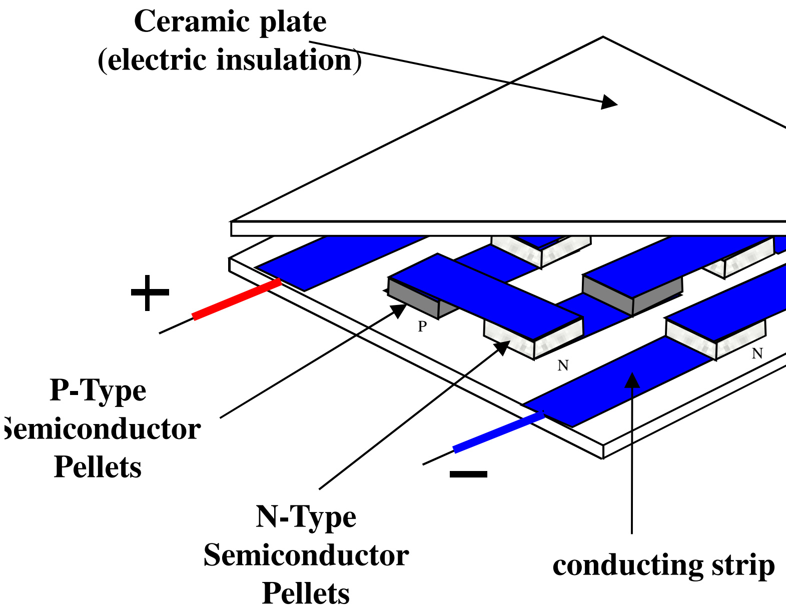
ZT is a very convenient figure for comparing the potential efficiency of devices using different materials.

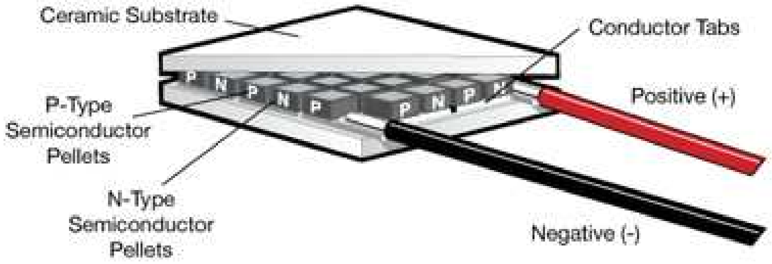
Values of ZT=1 are considered good

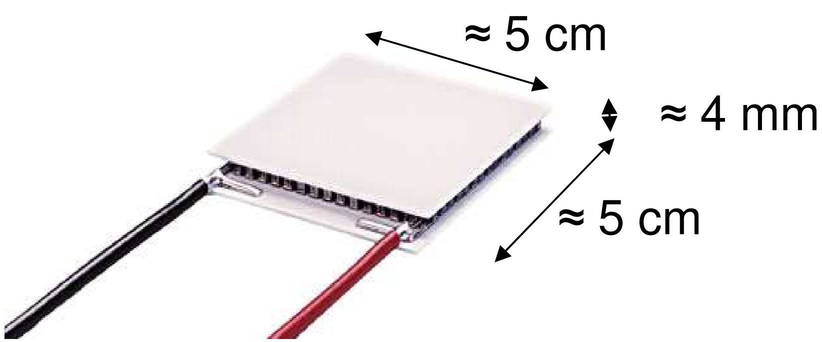
Bi_2Te_3 ZT is about 1

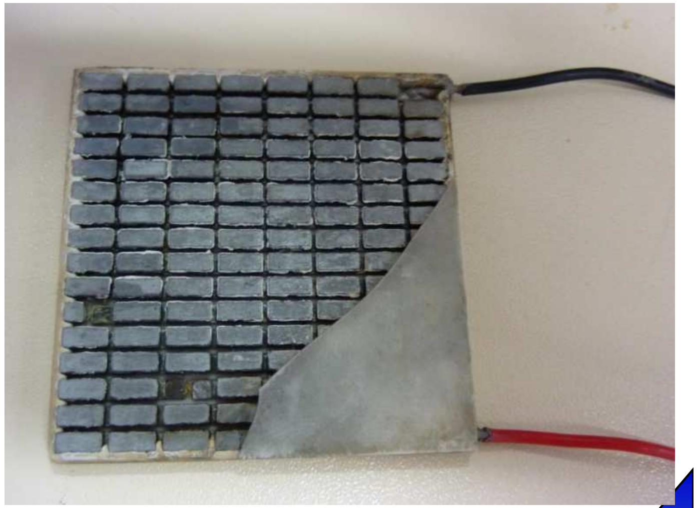
elements of a thermoelectric generator

- **TE modules**
  individual couples connected electrically in series
  Thermally in parrallel to enhance the effect
  Semiconductor P and N







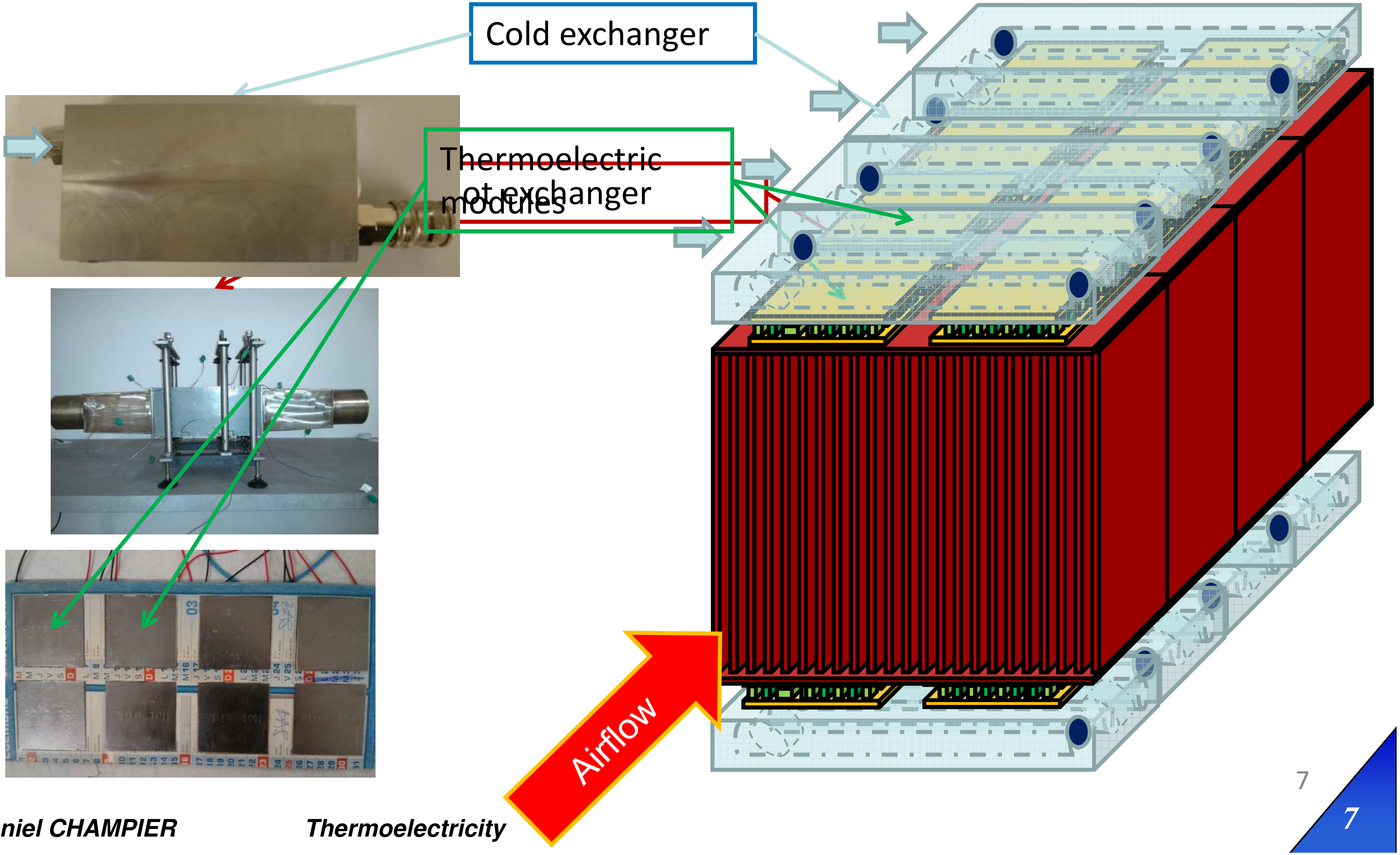


elements of a thermoelectric generator

Advantages of thermoelectric modules

- **Direct Energy Conversion**
- **No Moving Parts**
- **No Working Fluids**
- **Maintenance-free Durability**
- **High reliability: solid state construction.**
- **Small size and weight.**
- **Electrically and acoustically "quiet" Operation**
- **Operation in any orientation : aerospace and moving applications.**
- **Extreme climatic conditions (hot, cold, wet, dry)**

Design of a ThermoElectric Generator TEG



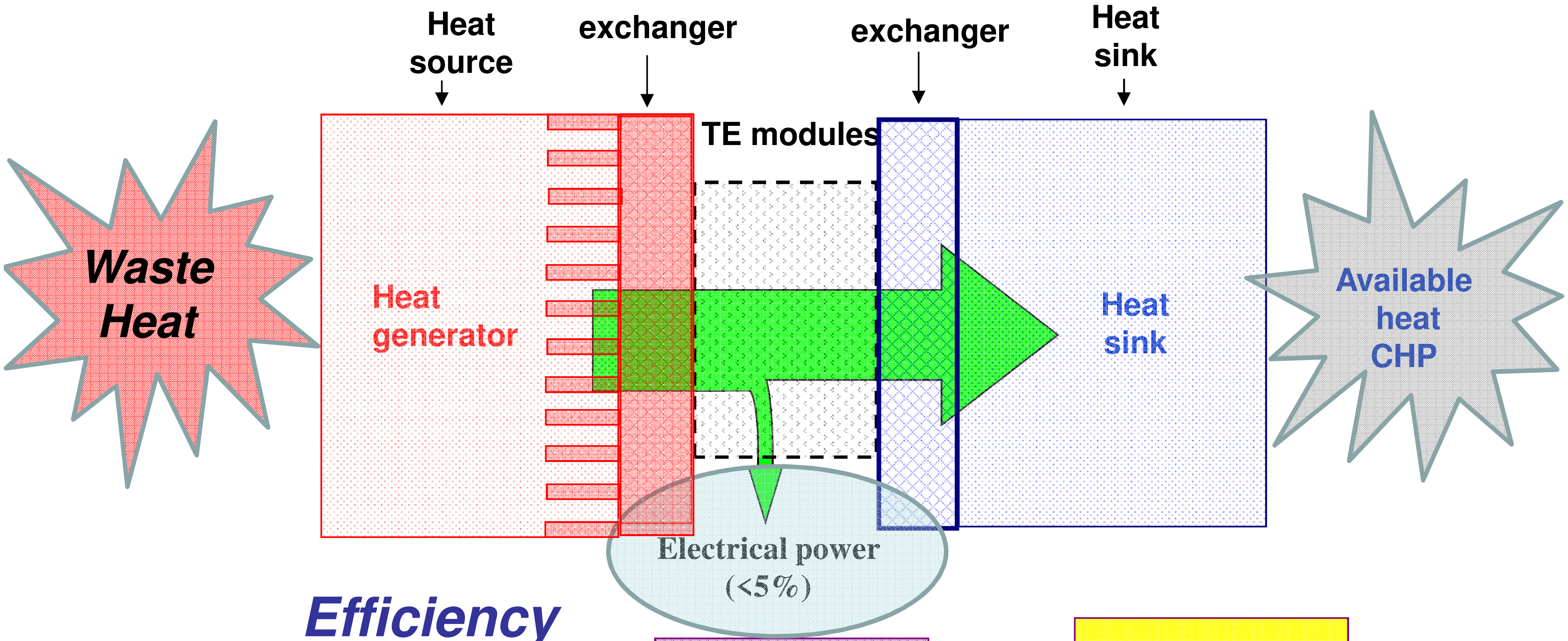
Cold exchanger

Thermoelectric modules

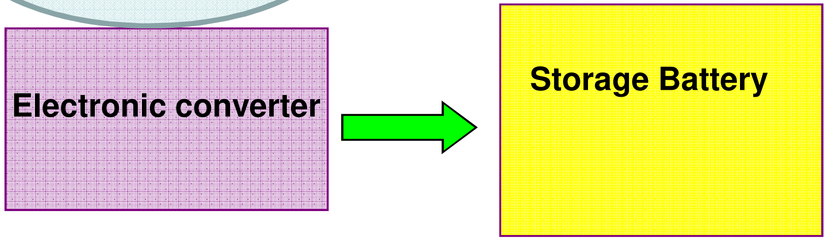
ot exchanger

Thermoelectric (TE) Generators TEG

convert directly a very small part of the heat moving through them into electricity



Efficiency is low

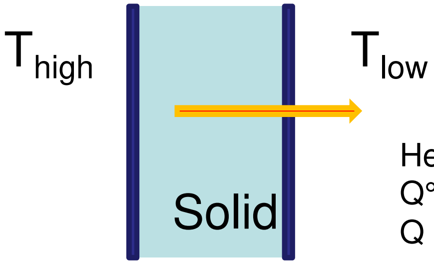


$$Pelec = \beta(\Delta T)^2$$

Generality about Heat Transfer

3 Heat Transfer Modes

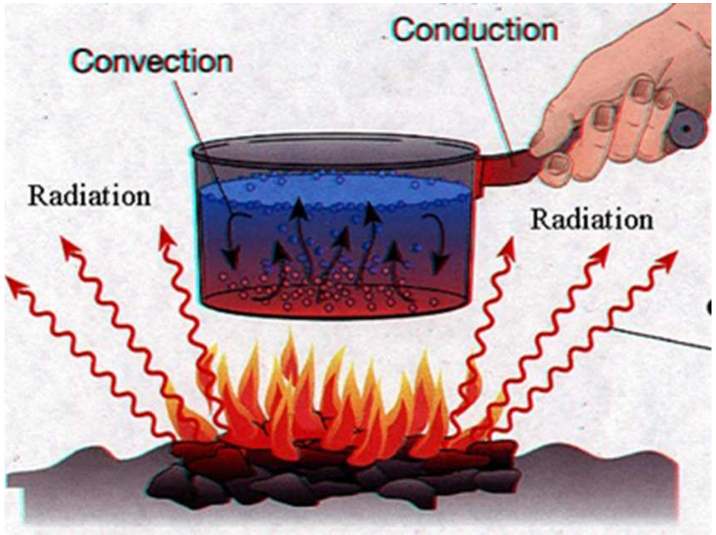
1) Conduction heat transfer



Heat “flows” to right
Q°= Φ heat transfer rate, watts
Q heat, Joules

2) Convection heat transfer : heat transfer due to a flowing fluid.
The fluid can be a gas or a liquid

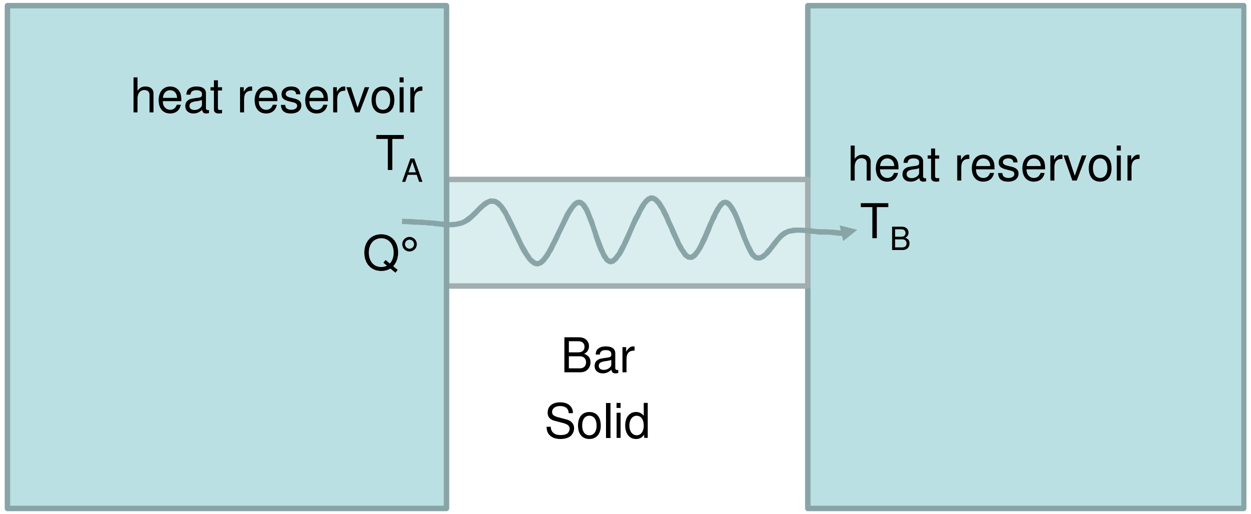
3) radiation : transmission of energy through space without the necessary presence of matter.



Picture: University of Wisconsin

Generality about Heat Transfer

Conduction heat transfer (steady state case)



Q°= Φ heat transfer rate (W) (flux de chaleur, puissance thermique, flux thermique) is a function of the temperature of the two reservoirs, the bar geometry and the bar properties.

$$\dot{Q} = \frac{\lambda.A}{L}(T_a-T_b)=\frac{(Ta-Tb)}{R_{th}}=G_{th}\ (T_a-T_b)$$

A area of the bar
L length of the bar
λ thermal conductivity ($W.m^{-1}K^{-1}$)
R_{th} Thermal resistance
G_{th} Thermal conductance

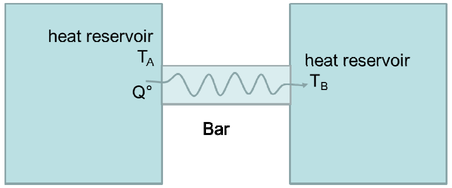
Metals	Ag	Cu	Al	Fe	Steel
λ [W/m-K]	420	390	200	70	50

Non-Metals	H_2O	Air	Brics	Wood	Cork
λ [W/m-K]	0.6	0.026	0.4-0.5	0.2	0,04

Solid means no moving particles

Generality about Heat Transfer

Analogy Heat transfer and Electricity

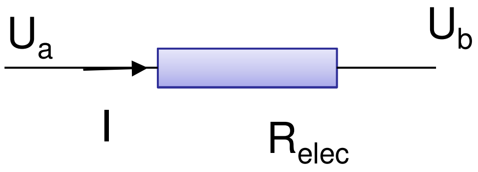


$$\dot{Q} = \frac{(Ta - Tb)}{R_{th}} \qquad (W)$$

$$R_{th} = \frac{L}{\lambda . A} \qquad (K.W^{-1})$$

λ thermal conductivity ($W.m^{-1}K^{-1}$)

Convection, radiation and loss are also here



$$I = \frac{(U_a - U_b)}{R}$$

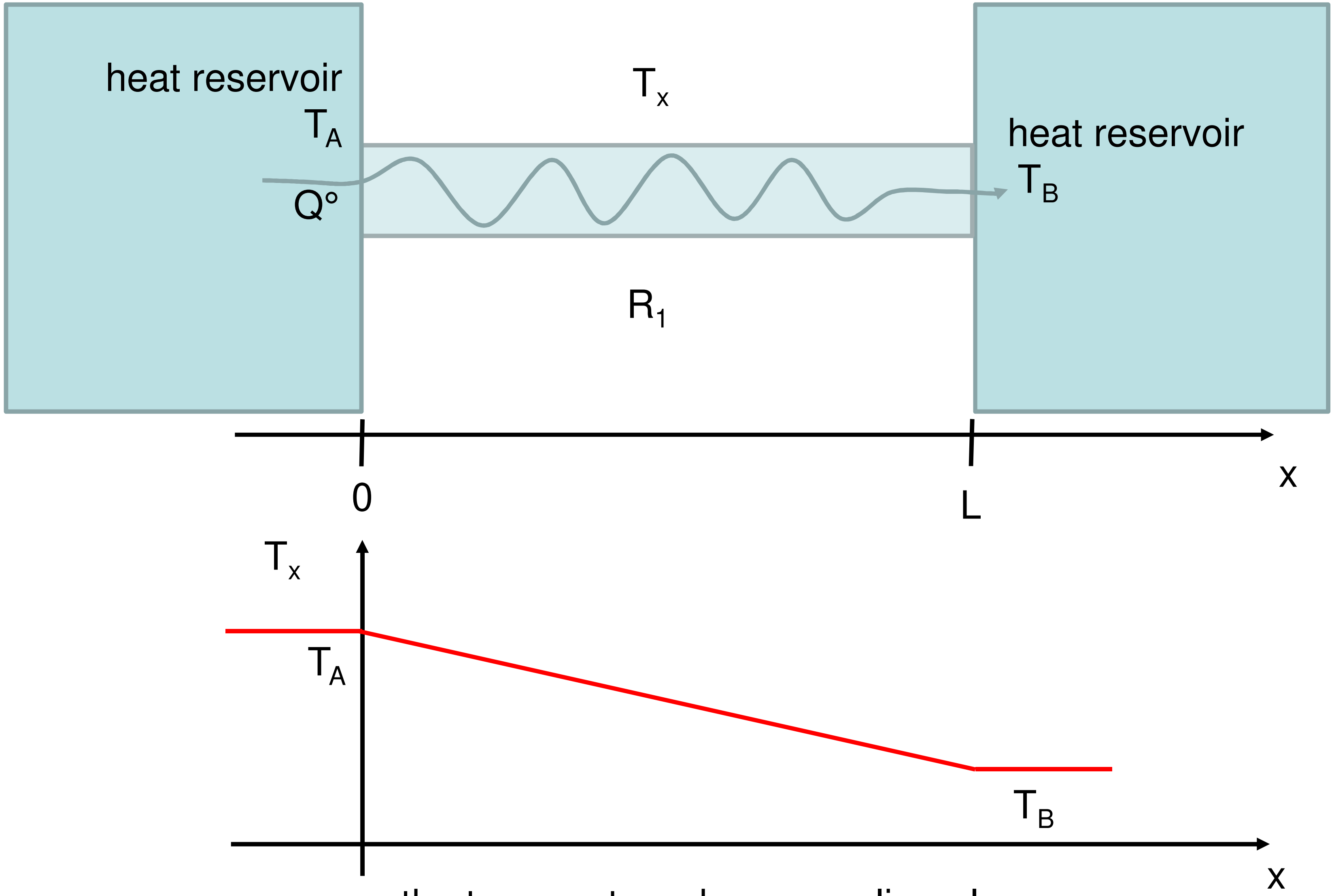
$$R_{elec} = \frac{\rho L}{A} = \frac{L}{\sigma . A}$$

σ electrical conductivity (S/m)

Almost perfect insulation

Generality about Heat Transfer

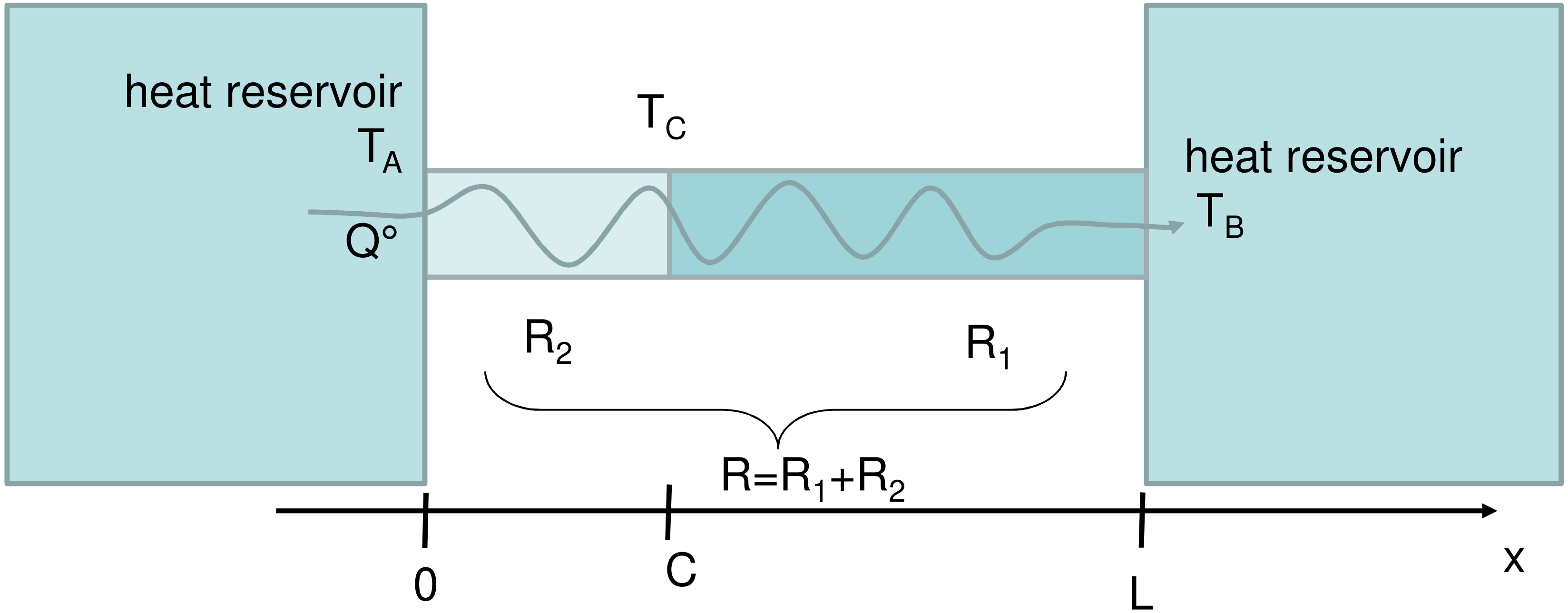
Conduction heat transfer (steady state case)



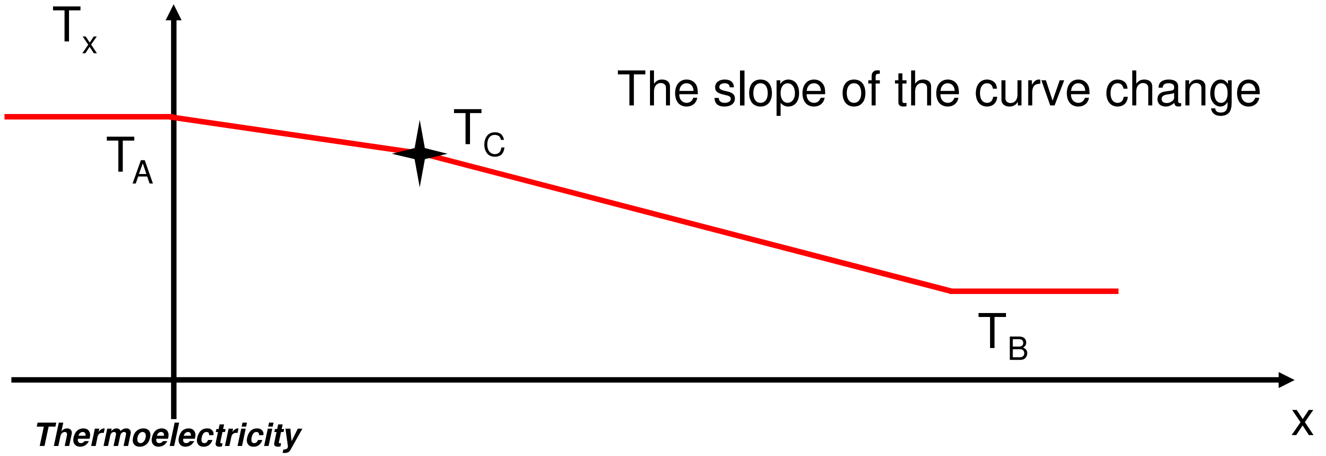
the temperature decreases linearly

Generality about Heat Transfer

Conduction heat transfer (steady state case)



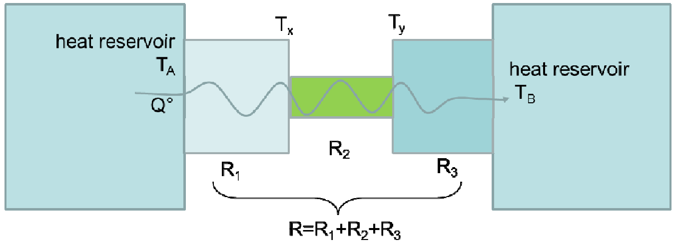
$$\dot{Q} = \frac{T_C - T_B}{R_1} = \frac{T_A - T_B}{R_1 + R_2} \qquad T_C - T_B = \frac{R_1}{R_1 + R_2}(T_A - T_B)$$

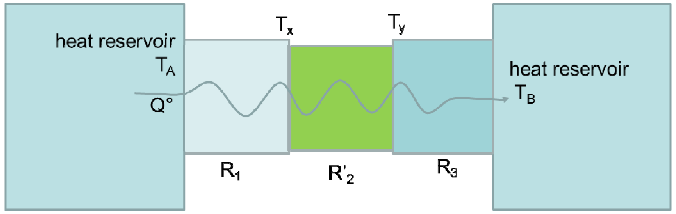


The slope of the curve change

Generality about Heat Transfer

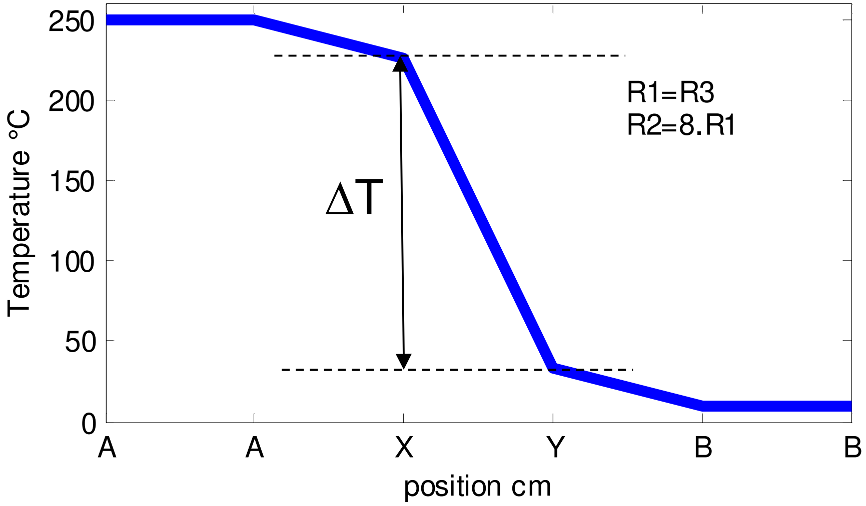
Conduction heat transfer (steady state case)

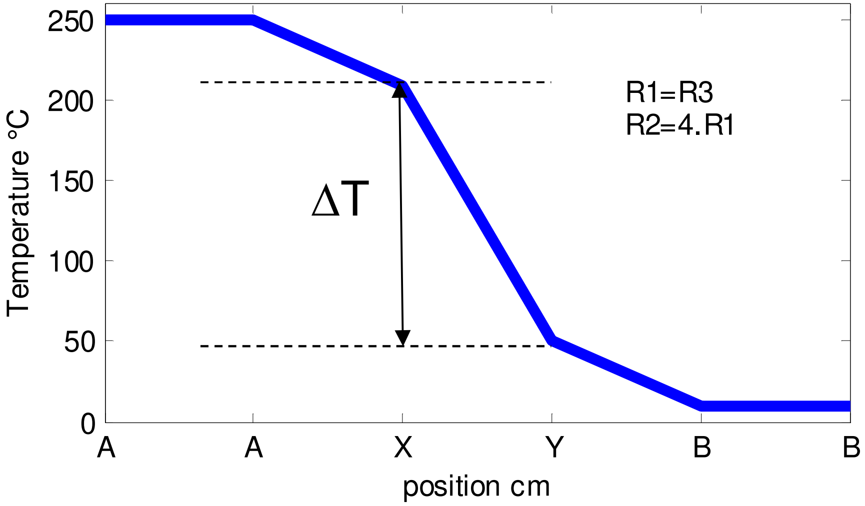




$$\dot{Q} = \frac{T_x - T_y}{R_2} = \frac{T_{A-}T_B}{R_1 + R_2 + R_3}$$

$$T_x - T_y = \frac{R_2}{R_1 + R_2 + R_3}(T_{A-}T_B)$$





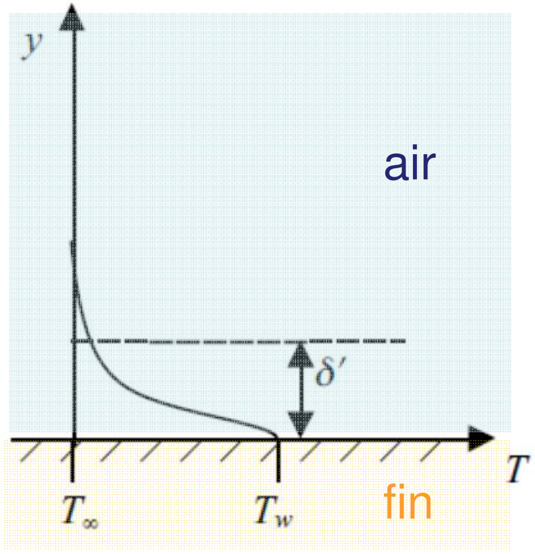
1 module P=K ΔT^2

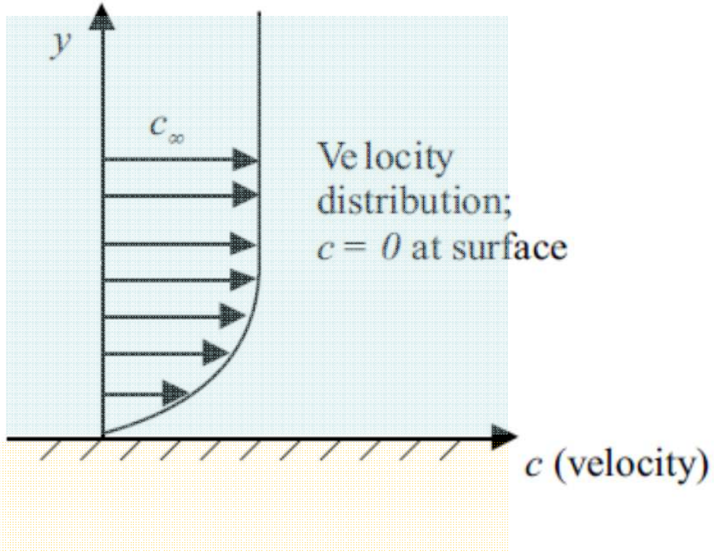
2 modules P=2K ΔT'^{2}

Generality about Heat Transfer

Convective heat transfer

air moving near a blade or a fin for example





Region of thickness δ′ : thin "film" of slowly moving fluid
→most of the temperature difference occurs.

Outside this layer, *T* is roughly uniform

$$\dot{Q} = h.A.(T_w - T_\infty)$$

h : convective heat transfer coefficient (W/m²K)
h is known mainly through experiments

Generality about Heat Transfer

Convective heat transfer

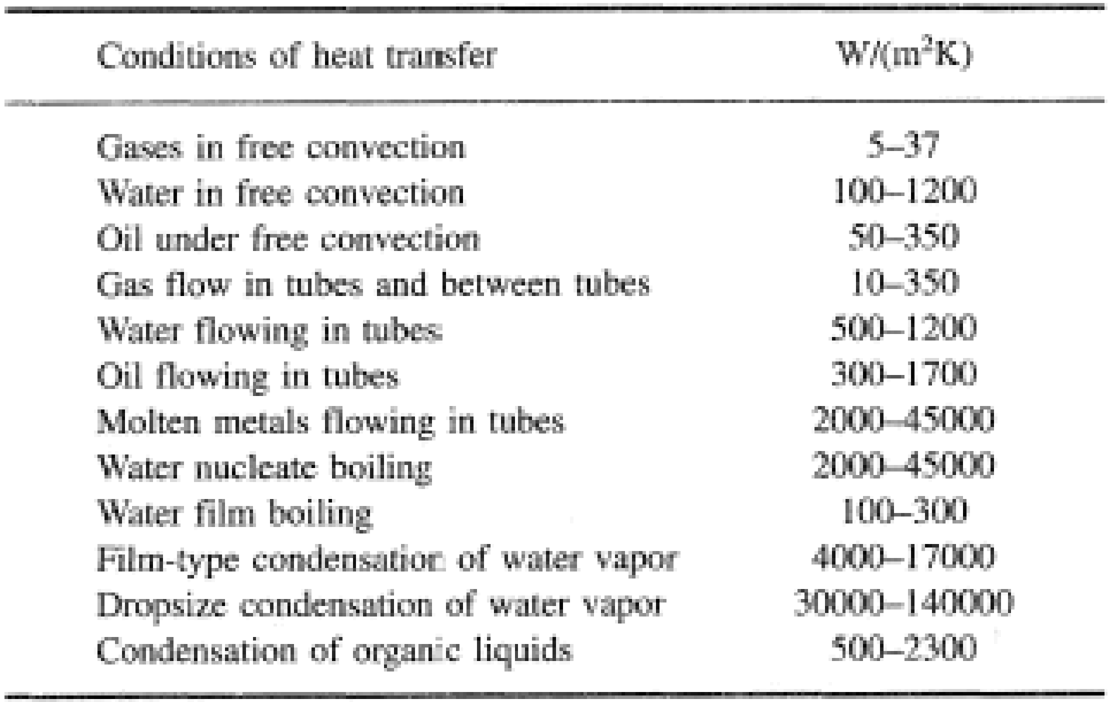
$$\dot{Q} = h.A.(T_w - T_\infty)$$

h : convective heat transfer coefficient (W/m²K)

h is known mainly through experiments

$$R_{th} = \frac{1}{h.A}$$

Typical values

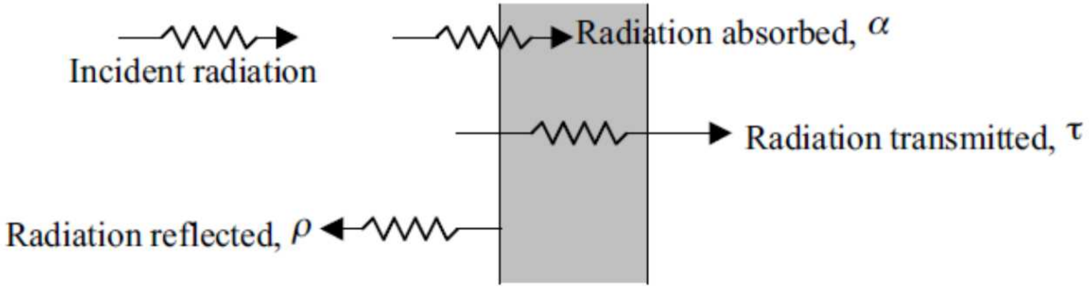


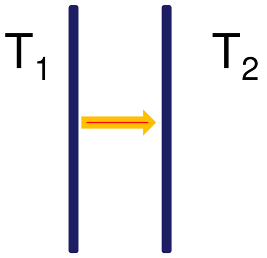
Conditions of heat transfer	W/(m²K)
Gases in free convection	5–37
Water in free convection	100–1200
Oil under free convection	50–350
Gas flow in tubes and between tubes	10–350
Water flowing in tubes	500–1200
Oil flowing in tubes	300–1700
Molten metals flowing in tubes	2000–45000
Water nucleate boiling	2000–45000
Water film boiling	100–300
Film-type condensation of water vapor	4000–17000
Dropsize condensation of water vapor	30000–140000
Condensation of organic liquids	500–2300

Generality about Heat Transfer

Radiation Heat Transfer

All bodies radiate energy in the form of photons moving in a random direction, with random phase and frequency. When radiated photons reach another surface, they may either be absorbed, reflected or transmitted.





transfer between gray, planar, surfaces

$$\dot{Q} = \frac{\sigma . A . (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

σ is the Stefan-Boltzmann constant
$\sigma = 5.67.10^{-8}$ W/m^2K^4
ε emissivity : property of material
T_1 and T_2 : Kelvin

Material	Emissivity
Aluminum polished	0.03
Aluminum Heavily oxidized	0.2 - 0.33
Asphalt	0.88
Brick	0.90
Concrete, rough	0.91
Copper, polished	0.04
Copper, oxidized	0.87
Paint	0.8 -0.96
Paper white	0.95 to 0.98

Maximun Power and Efficiency

These results will be explained in detail later

Electrical Power

$$W_{elec}^{Max} = \Delta T^2 \;.\; \frac{N.A}{8L} \;.\; \sigma \;.\; \alpha^2$$

"power factor" :
type of TE material

Dependence upon the temperature difference across the thermoelements

Construction :
- number of thermoelements
- cross-sectional area
- length of each element.

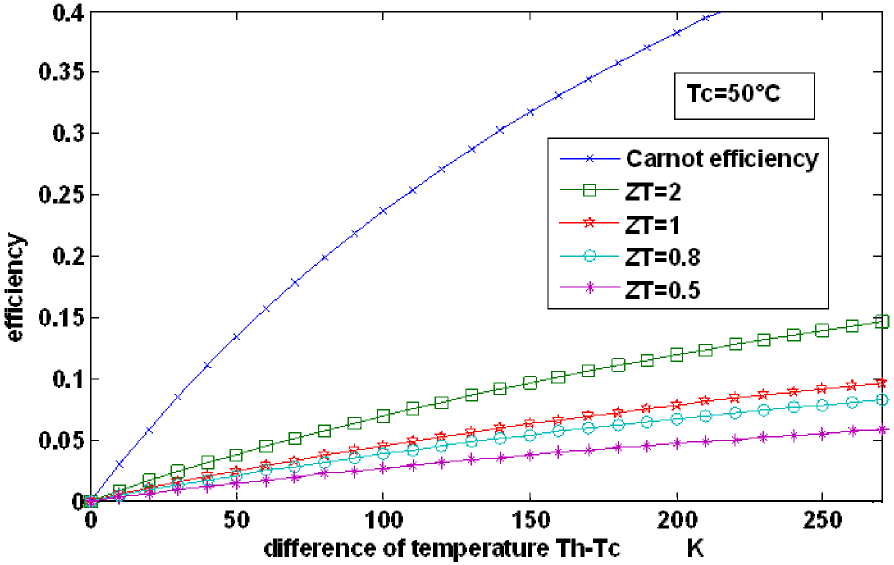
Efficiency

$$\eta_{max} = \frac{W_{elec}}{\Phi_{thermal}} = \frac{\Delta T}{Th} \cdot \frac{\sqrt{1+zT} - 1}{\sqrt{1+zT} + \frac{Tc}{Th}}$$

Efficiency is a function of **zT**

$$z = \frac{\alpha^2}{\rho\lambda} = \frac{\sigma.\alpha^2}{\lambda} \qquad T = \frac{(Th+Tc)}{2}$$

Efficiency is low

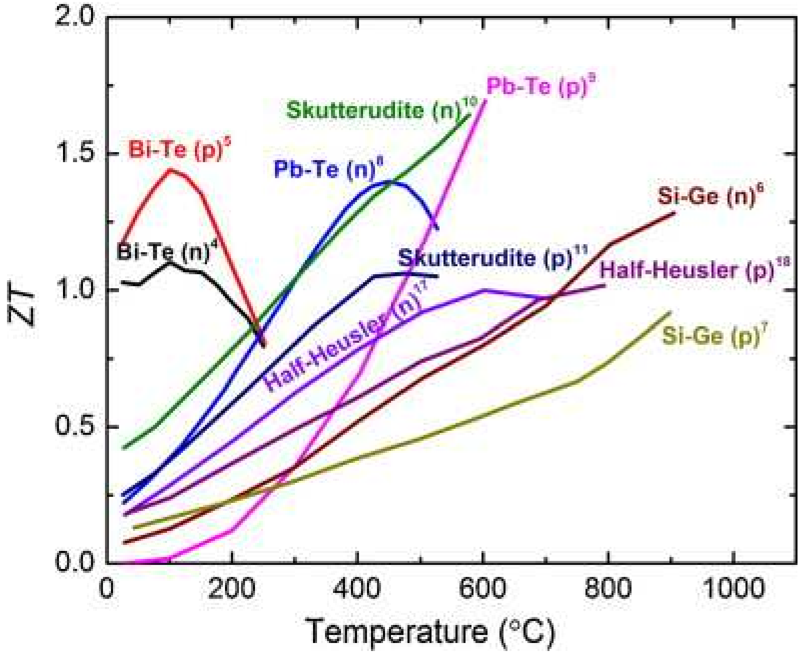


Main goals

- Augment ZT
- Augment ΔT

ZT of Materials

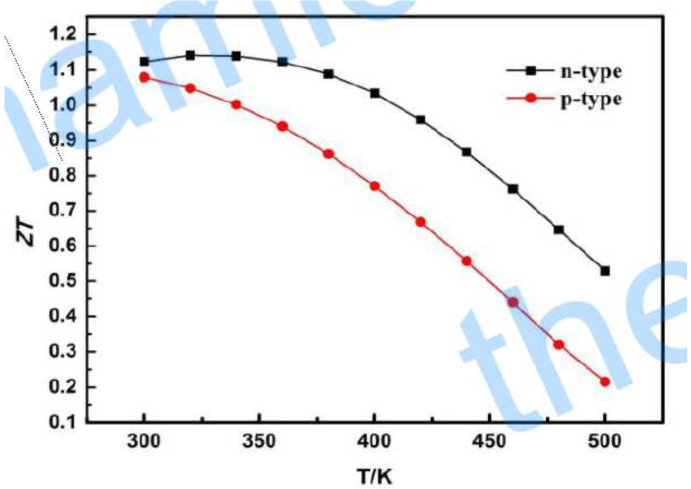
Laboratory



Overview of ZT vs temperature
for different thermoelectric materials *

Industry

Industrial ingot (Thermonamic 2015)

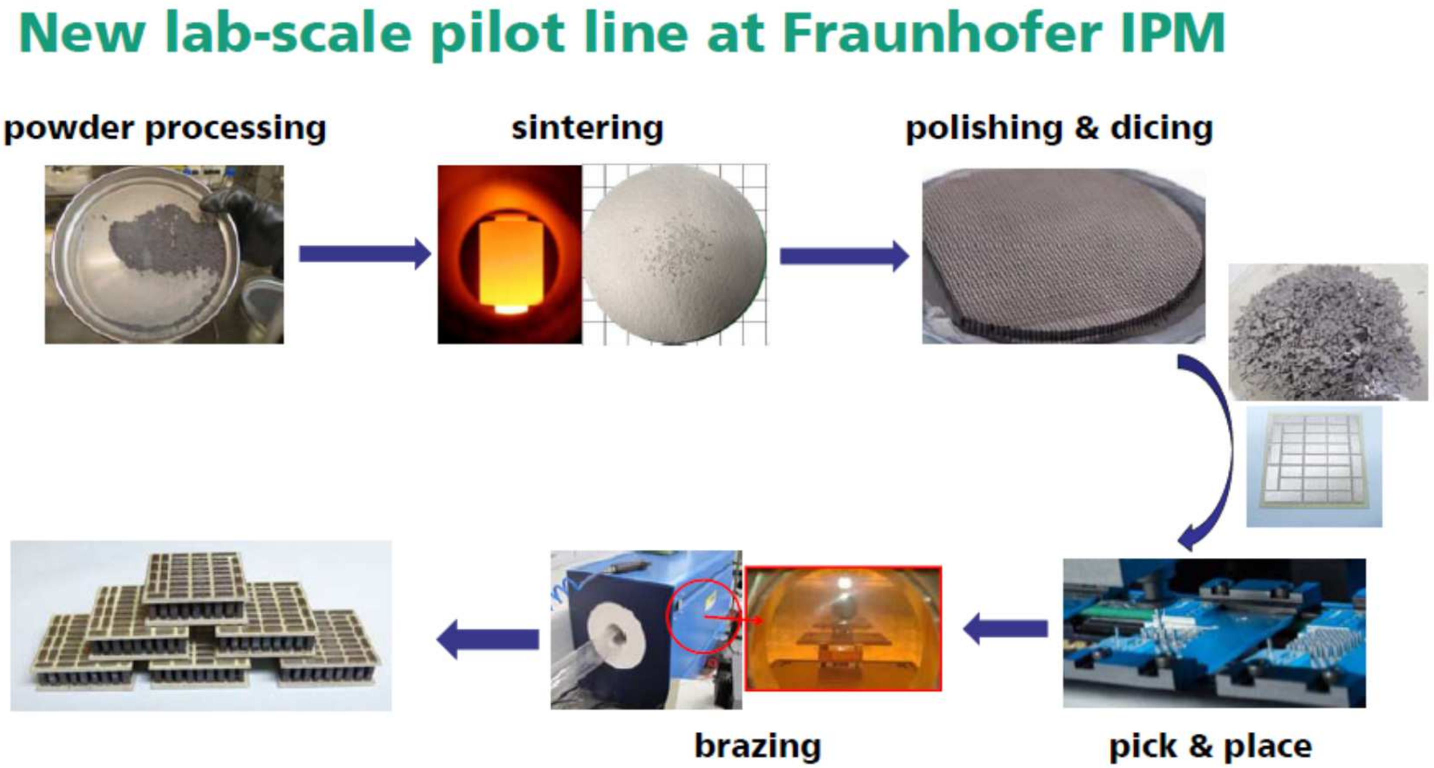


ZT values of the Bi_2Te_3-based ingot

Bi_2Te_3 ZT is about 1
the only commercial module available at large scale

** Shuo Chen, Zhifeng Ren Recent progress of half-Heusler for moderate temperature thermoelectric applications materialstoday*

From materials to modules
Example of production in laboratory



Thermoelectric modules (TEM) based on half-Heusler compounds

* *Lab-scale pilot line for Thermoelectric Modules based on half-Heusler Compounds J. D. König, M. Kluge, K. Bartholomé, E. Geczi, U. Vetter, M. Vergez, U. Nussel, K. R. Tarantik*

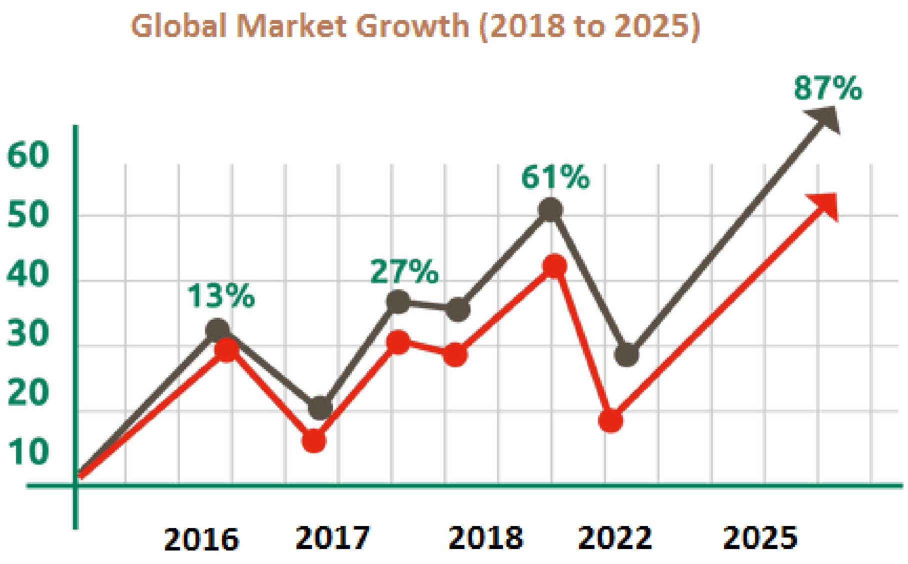
Industrial modules

manufacturer	Materials	ΔT	Power	state	T Max	
HiZ, Thermonamic, Lairdtech, Marlow, etc.	$Bi_2 Te_3$	300 K	20 W	40€-100€	300 °C	historical Scarce
Evident Thermoelectric IsabellenHütte	Half Heusler	500 K	15W	Coming soon Lab available	600°C	environmental-friendly, low cost, availability of raw materials
Shanghai Institute of Ceramics	skuterrudites	510 K	25W	Coming soon	600°C	environmental-friendly, low cost, availability of raw materials
TEGMA	skuterrudites			Coming soon		
TEGNOLOGY	Zn_4Sb_3/Mg_2SiSn Zintl Phase	105 K	9 mW	Available 100€	125°C	
TECTEG MFR	Calcium/Manganese oxide	750 K	12.3W	Available 360$	800°C	environmental-friendly, low cost, availability of raw materials. Weight : 6g
TECTEG MFR cascade modules	Calcium/Manganese oxides with Bi2Te3	435 K	11 W	Available 560$	600°C	
Hotblock Onboard	silicon based alloy	500 K	3.6W	Available 200€	600°C	environmental-friendly, low cost, availability of raw materials. Weight : 6g
~~Romny Scientific~~	magnesium silicide					low $/Watt
~~Alphabet Energy~~	p-type tetrahedrites n-type magnesium silicide (Mg2Si)			~~Coming soon~~		Tetrahedrite is a naturally occurring p-type mineral
	Organics TEG	low		Still in lab	130°	

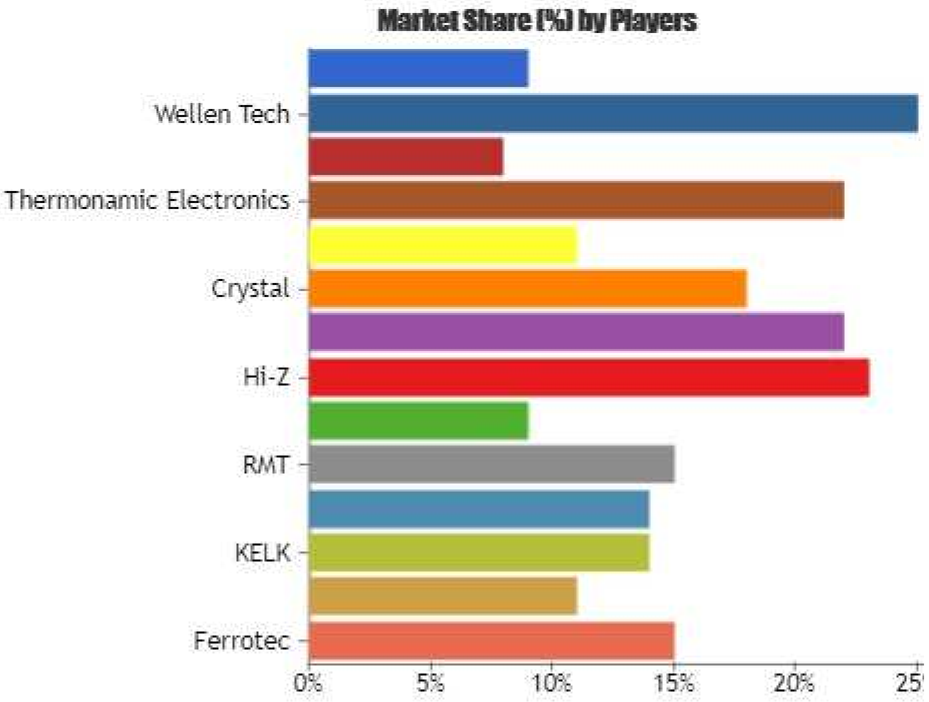
Market for TEG

Global Thermoelectric Generator (TEG) Modules Sales Market Research Report 2018 to 2025

Published (2018) By: QY RESEARCH



Thermoelectric Modules Market- Leader



Nidhi Bhawsar June 26, 2018

List of Thermoelectric / Peltier Manufactures, Companies and Suppliers major manufacturers

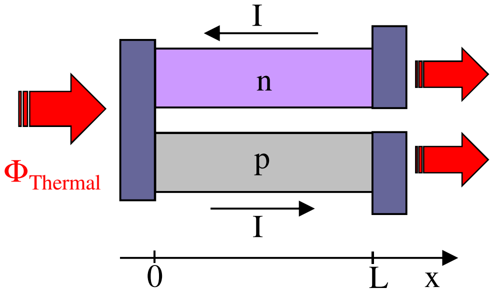
- Applied Thermoelectric Solutions LLC
- Acal BFI
- Adcol Electronic
- ADV Engineering
- Alflex Technologies
- Align Sourcing
- Ambient Micro
- AMS Technologies
- Analog Technologies
- Asia Inno
- Beijing Huimao Cooling Co., Ltd.
- Bentek Systems
- BTS Europe
- Cidete Ingenieros SL
- CUI
- Custom Thermoelectric Inc.
- Crystal LTD.
- European Thermodynamics
- Everredtronics Ltd.
- Ferrotec Corporation
- Gentherm
- Gentherm Global Power
- Green TEG AG
- Guang Dong Fuxin Electronic
- Hangzhou Aurin Cooling
- Hebei IT
- Hicooltec Electronic
- Hi-Z Technology, Inc
- HotBlock OnBoard
- Hui mao
- Interm
- Kelk Ltd.
- Kryotherm
- Laird Tech Inc.
- II-VI Marlow
- INB Thermoelectric
- ISA Impex
- Innoveco
- Merit Technology Group
- Micropelt GmbH
- Newmark International
- OTE International
- P&N Tech
- Perpetua Power
- Phononic
- Qinhuangdao Fulianjing
- Quick Cool
- RFI Corp.
- RMT LTD
- Sheetak
- S&PF Modul
- Taicang TE Cooler
- TE Technology, Inc.
- TEC Microsystems
- TECTEG
- TEGEOS
- TEGPRO Thermoelectric Generator
- Termo-Gen AB
- Thermal Electronics
- Thermalforce
- Thermion Company
- Thermix
- Thermonamic Electronics
- Tybang Electronics
- UWE Electronic
- Wellen Tech
- WeTEC
- Yamaha
- Z-max

Modeling of thermoelectric modules

Simplified Thermoelectric Equations and properties

Assumptions:
The material properties are temperature independent
Calculations will be made in steady state conditions

Thermoelectric equations (single couple)



Assumption :
all the heat flow between the source and sink takes place within the thermocouple.
Thermal radiation and losses by conduction and convection through the surrounding medium are negligible.
The two thermocouple branches in our model have constant cross-sectional areas.
Thomson effects neglected.

For each branch of the thermoelectric module we have one thermoelectric flow (Peltier) and a heat flow (conduction) :

$$\begin{aligned}\Phi_p &= \Pi_p \times I - \lambda_p \times S_p \times \frac{dT}{dx} = \alpha_p \times I \times T - \lambda_p \times S_p \times \frac{dT}{dx} \\ \Phi_n &= -\alpha_n \times I \times T - \lambda_n \times S_n \times \frac{dT}{dx}\end{aligned} \qquad (1)$$

λ is the thermal conductivity of the material [W. m^{-1}. K^{-1}],

Π is the Peltier coefficient of the material [V]

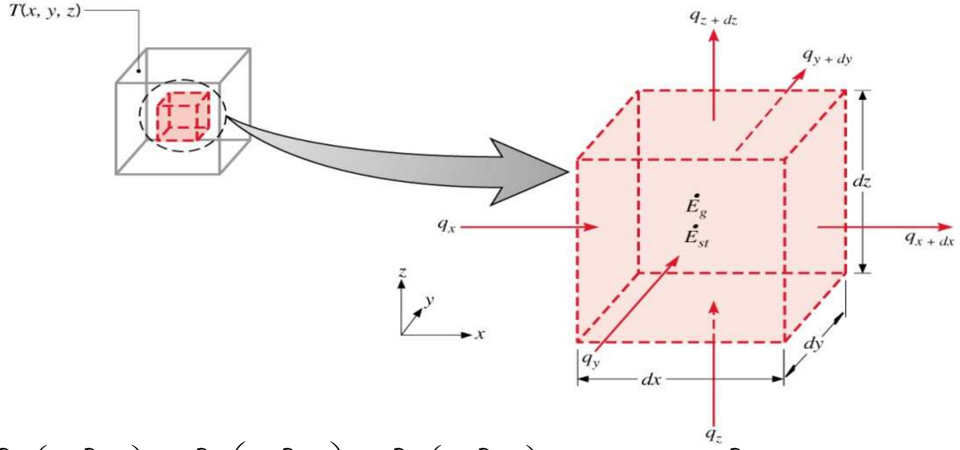
α is the Seebeck coefficient of the material [V. K^{-1}]

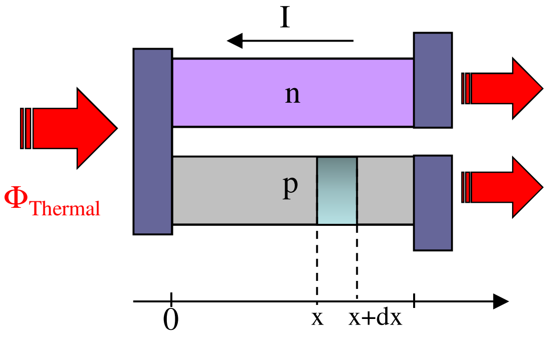
I is the norm of the electric current [A] which explains the minus sign in front.

Thermoelectric equations (single couple)

conservation of energy to a differential control volume through which energy transfer is exclusively by conduction.

Heat equation in Cartesian Coordinates:





control volume : a slice along x

$$\underbrace{\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)}+\phi=\rho_m c_p\frac{\partial T}{\partial t}$$

Net transfer of thermal energy into the control volume (inflow-outflow)

Thermal energy generation

Change in thermal energy storage

ρ_m is the specific weight

Cp is the specific heat capacity

ϕ is the power density

All the heat flow between the source and sink takes place within the thermocouple.
Thus, thermal radiation and losses by conduction and convection through the surrounding medium are negligible.

It is therefore possible to neglect the temperature variations along the axes y and z.

All this brings us to solve a one-dimensional problem along the x axis

The heat equation can be written in this case

$$\frac{\partial^2 T}{\partial x^2}+\frac{\phi}{\lambda}=\frac{1}{a}\times\frac{\partial T}{\partial t}$$

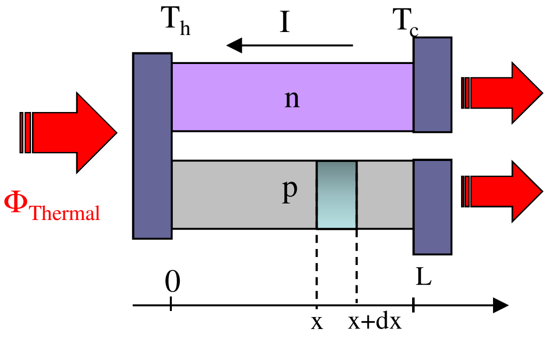
$a = \lambda / c_p.\rho$ is the thermal diffusivity

with $\emptyset=\rho\frac{dx}{dz.dy}\cdot I^2\cdot\frac{1}{dx.dy.dz}=\frac{\rho}{S^2}I^2\left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]$ heat generation by Joule effect

ρ is the electrical resistivity

S is the section of a leg

Thermoelectric equations (single couple)



heat equation $$\frac{1}{a}\times\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}+\frac{\phi}{\lambda}$$ with $$\phi=\frac{I^2\times\rho}{S^2}$$

Steady state. The left term disappears. $$0=\frac{\partial^2 T}{\partial x^2}+\frac{\phi}{\lambda}=\frac{\partial^2 T}{\partial x^2}+\frac{I^2\times\rho}{\lambda.S^2}$$

We have for each leg: $$-\lambda_p\times S_p\times\frac{\partial^2 T}{\partial x^2}=\frac{I^2\times\rho_p}{S_p}$$ **and** $$-\lambda_n\times S_n\times\frac{\partial^2 T}{\partial x^2}=\frac{I^2\times\rho_n}{S_n} \qquad (2)$$

If we solve equation 2 for the branch p :

$$\lambda_p\times S_p\times\frac{\partial T}{\partial x}=-\left(\frac{I^2\times\rho_p}{S_p}\right)x+B \qquad \textbf{(3a)}$$

$$\lambda_p\times S_p\times T(x)=-\left(\frac{I^2\times\rho_p}{2\times S_p}\right)x^2+Bx+C \qquad \textbf{(3b)}$$

Boundary conditions: $T(x=0)=Th$ and $T(x=L)=Tc$

for x = 0 we have : $C=\lambda_p\times S_p\times Th$

for $x=L_p$ we have $$\lambda_p\times S_p\times Tc=-\left(\frac{I^2\times\rho_p\times L_p^2}{2\times S_p}\right)+B\times L_p+\lambda_p\times S_p\times Th$$

$$B=\frac{\lambda_p\times S_p\times(Tc-Th)}{L_p}+\left(\frac{I^2\times\rho_p\times L_p}{2\times S_p}\right)$$

If we replace B in (3a)

$$\lambda_p\times S_p\times\frac{\partial T}{\partial x}=-\left(\frac{I^2\times\rho_p\times\left(x-\frac{L_p}{2}\right)}{S_p}\right)+\frac{\lambda_p\times S_p\times(Tc-Th)}{L_p} \qquad (4.1)$$

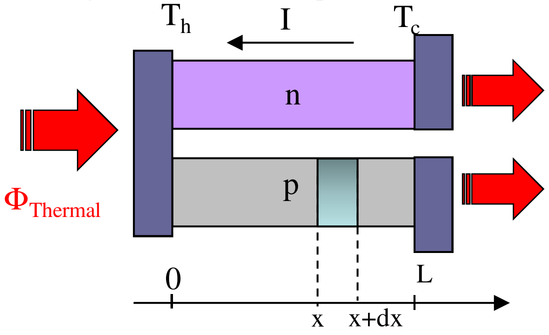
and if we follow the same reasoning for the N-doped leg

$$\lambda_n\times S_n\times\frac{\partial T}{\partial x}=-\left(\frac{I^2\times\rho_n\times\left(x-\frac{L_n}{2}\right)}{S_n}\right)+\frac{\lambda_n\times S_n\times(Tc-Th)}{L_n} \qquad (4.2)$$

Thermoelectric equations (single couple)

$$\Phi_p = \alpha_p \times I \times T - \lambda_p \times S_p \times \frac{dT}{dx} \quad (1)$$

$$\lambda_p \times S_p \times \frac{\partial T}{\partial x} = -\left(\frac{I^2 \times \rho_p \times \left(x - \frac{L_p}{2} \right)}{S_p} \right) + \frac{\lambda_p \times S_p \times (Tc - Th)}{L_p} \quad (4.1)$$



By combining (1) and (4):

$$\begin{aligned}
\Phi_p &= \alpha_p \times I \times T + \frac{I^2 \times \rho_p \times \left(x - \frac{L_p}{2} \right)}{S_p} - \frac{\lambda_p \times S_p \times (Tc - Th)}{L_p} \\
\Phi_p (x = 0) &= \alpha_p \times I \times Th - \frac{I^2 \times \rho_p \times L_p}{2 \times S_p} - \frac{\lambda_p \times S_p \times (Tc - Th)}{L_p} \\
\Phi_p \left(x = L_p \right) &= \alpha_p \times I \times Tc + \frac{I^2 \times \rho_p \times L_p}{2 \times S_p} - \frac{\lambda_p \times S_p \times (Tc - Th)}{L_p}
\end{aligned}$$

$$\begin{aligned}
\Phi_n &= -\alpha_n \times I \times T + \frac{I^2 \times \rho_n \times \left(x - \frac{L_n}{2} \right)}{S_n} - \frac{\lambda_n \times S_n \times (Tc - Th)}{L_n} \\
\Phi_n (x = 0) &= -\alpha_n \times I \times Th - \frac{I^2 \times \rho_n \times L_n}{2 \times S_n} - \frac{\lambda_n \times S_n \times (Tc - Th)}{L_n} \\
\Phi_n \left(x = L_p \right) &= -\alpha_n \times I \times Tc + \frac{I^2 \times \rho_n \times L_n}{2 \times S_n} - \frac{\lambda_n \times S_p \times (Tc - Th)}{L_n}
\end{aligned}$$

⇨

If we sum $\Phi_p (x = 0)$ and $\Phi_n (x = 0)$ we get the power at the hot side of the system Φ_h.

Similarly if we sum $\Phi_p (x = L)$ and $\Phi_p (x = L)$ we obtain the power at the cold side Φ_c .

$$\Phi_h = \left(\alpha_p - \alpha_n \right) \times I \times Th - \left(\frac{\rho_n \times L_n}{S_n} + \frac{\rho_p \times L_p}{S_p} \right) \frac{I^2}{2} - \left(\frac{\lambda_n \times S_n}{L_n} + \frac{\lambda_p \times S_p}{L_p} \right) \times (Tc - Th)$$

$$\Phi_c = \left(\alpha_p - \alpha_n \right) \times I \times Tc + \left(\frac{\rho_n \times L_n}{S_n} + \frac{\rho_p \times L_p}{S_p} \right) \frac{I^2}{2} - \left(\frac{\lambda_n \times S_n}{L_n} + \frac{\lambda_p \times S_p}{L_p} \right) \times (Tc - Th)$$

$$W_{elec} = \Phi_h - \Phi_c = \left(\alpha_p - \alpha_n \right) \times I \times (Th - Tc) - r \times I^2$$

⇩

Simplified Thermoelectric Equations for a single couple

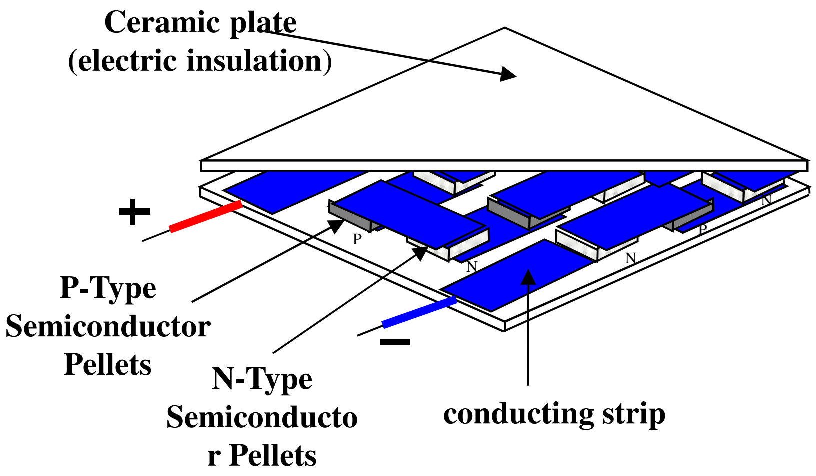
With $r = \frac{\rho_n \times L_n}{S_n} + \frac{\rho_p \times L_p}{S_p}$ the electrical resistance of a pair of legs PN.

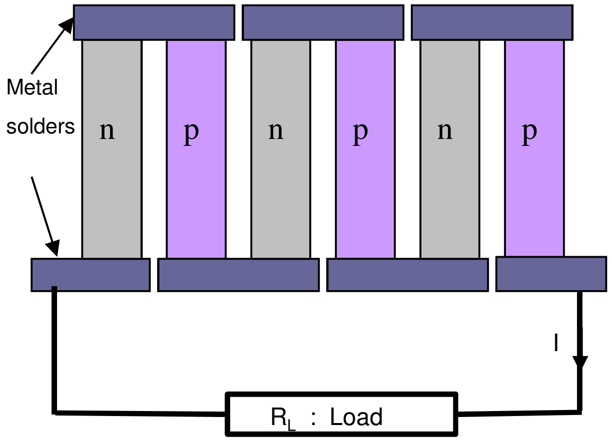
$k = \frac{\lambda_n \times S_n}{L_n} + \frac{\lambda_p \times S_p}{L_p}$ the overall heat transfer coefficient of a pair of legs PN.

$\alpha = \alpha_p - \alpha_n$ the Seebeck coefficient of the thermocouple PN

$$\begin{aligned}
\Phi_h &= \alpha \times I \times Th - \frac{r \times I^2}{2} + k \times (Th - Tc) \\
\Phi_c &= \alpha \times I \times Tc + \frac{r \times I^2}{2} + k \times (Th - Tc) \\
W_{elec} &= \alpha \times I \times (Th - Tc) - r \times I^2
\end{aligned}$$

Thermoelectric equations (modules)





The n-type and p-type thermoelements are electrically connected in serie by a conductor, and thermally in parallel.

The conductor is assumed to have negligible electrical resistance and thermal resistance.

$$\Phi_h = N.\left(\alpha \times I \times Th - \frac{r \times I^2}{2} + k \times (Th - Tc)\right)$$

$$\Phi_c = N.\left(\alpha \times I \times Tc + \frac{r \times I^2}{2} + k \times (Th - Tc)\right)$$

$$W_{elec} = N.\left(\alpha \times I \times (Th - Tc) - r \times I^2\right)$$

$$r = \frac{\rho_n \times L_n}{S_n} + \frac{\rho_p \times L_p}{S_p} \qquad k = \frac{\lambda_n \times S_n}{L_n} + \frac{\lambda_p \times S_p}{L_p}$$

$$\alpha = \alpha_p - \alpha_n$$

N number of couples (2N legs)

Assuming that the cross sections of the legs are the same $(S_n = S_p)$ and considering the leg lengths equal $(L_n = L_p)$ we can write:

$$K = N\frac{(\lambda_n + \lambda_p) \times S}{L} \qquad R = N\frac{(\rho_n + \rho_p) \times L}{S}$$

Simplified Thermoelectric Equations for a module

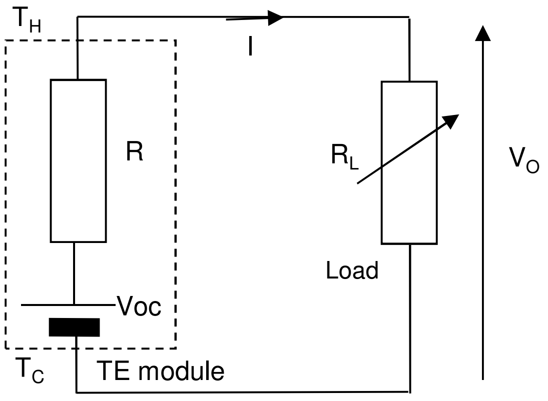
$$\Phi_h = N.\alpha \times I \times Th - \frac{R \times I^2}{2} + K \times (Th - Tc)$$

$$\Phi_c = N.\alpha \times I \times Tc + \frac{R \times I^2}{2} + K \times (Th - Tc)$$

$$W_{elec} = N.\alpha \times I \times (Th - Tc) - R \times I^2$$

Electrical model of TE module

$$\boxed{W_{elec} = N.\alpha \times I \times (Th - Tc) - R \times I^2}$$



The module can be modeled as a voltage source V_{oc} with internal resistance R

$$Voc = N.\alpha(Th - Tc) \qquad R = N\frac{(\rho_{n+}\rho_p) \times L}{S}$$

A load resistor R_L is connected to the module

$$I = \frac{V_{oc}}{R + R_L} = \frac{N.\alpha(Th - Tc)}{R + R_L} = \frac{N.\alpha.\Delta T}{R + R_L}$$

W_{elec} can also be written :

$$\boxed{Welec = R_L.I^2 = \frac{R_L}{(R + R_L)^2} N^2.\alpha^2.\Delta T^2}$$

Maximizing power output from a module

By differentiating Welec with respect to R_L we can find the value of load resistance that gives the maximum output power.

$$\frac{\partial Welec}{\partial R_L} = \frac{(R - R_L)}{(R + R_L)^3} N^2.\alpha^2.\Delta T^2 = 0$$

Adapted load $\mathbf{R_L = R}$

we can find the the maximum output power.

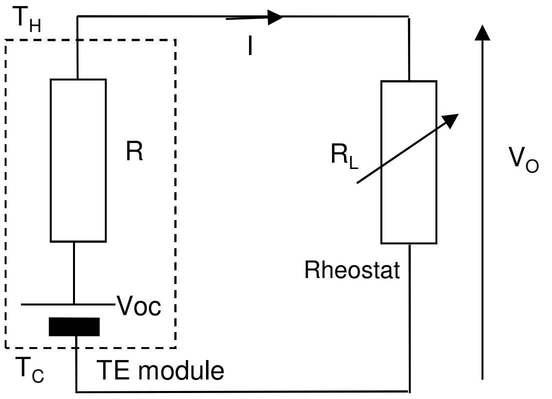
$$W_{elec}^{Max} = \frac{N^2.\alpha^2.\Delta T^2}{4.R} = \Delta T^2 \frac{N.S}{4L(\rho_{n+}\rho_p)}\alpha^2 = \Delta T^2.\frac{N.S}{8L}.\frac{2}{(\rho_{n+}\rho_p)}\alpha^2 = \Delta T^2.\frac{N.S}{8L}.\frac{\alpha^2}{\rho_{pn}} = \Delta T^2.\frac{N.S}{8L}.\sigma_{pn}\alpha^2$$

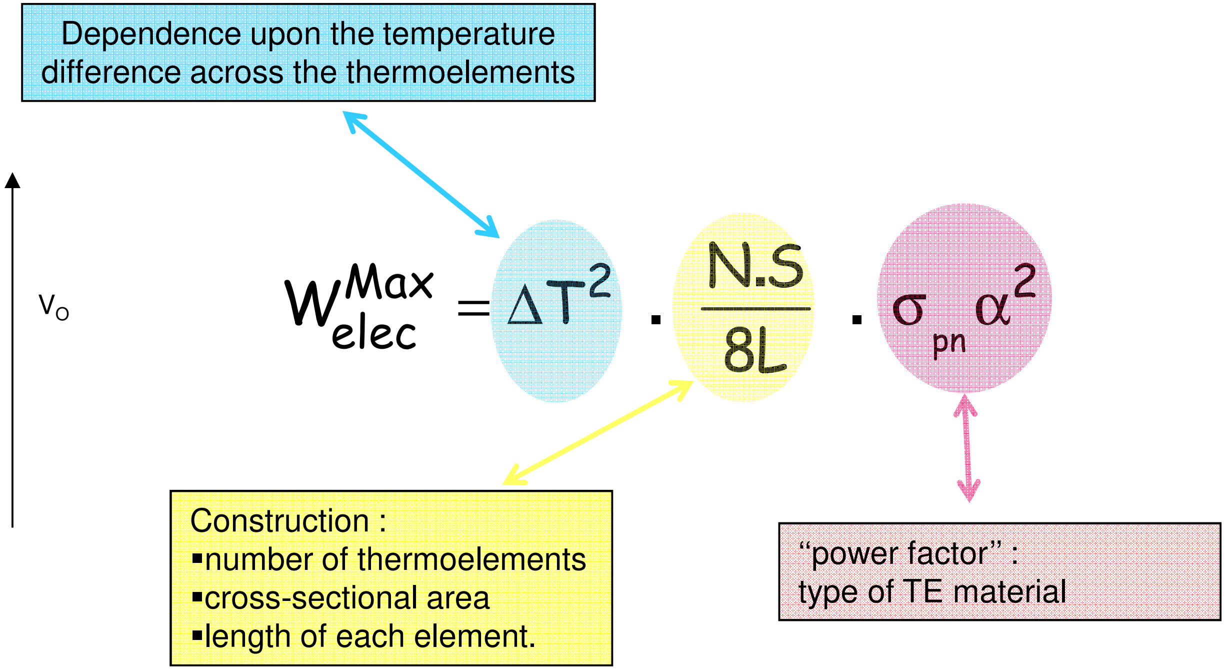
$$R = \frac{N(\rho_{n+}\rho_p) \times L}{S}$$

$$\rho_{pn} = \frac{\rho_{n+}\rho_p}{2}$$

$$\sigma_{pn} = \frac{1}{\rho_{pn}} = \frac{2\sigma_p\sigma_n}{\sigma_p + \sigma_n}$$

Maximizing power output from a module





Dependence upon the temperature difference across the thermoelements

$$W_{elec}^{Max} = \Delta T^2 \cdot \frac{N.S}{8L} \cdot \sigma_{pn}\,\alpha^2$$

Construction :
- ▪number of thermoelements
- ▪cross-sectional area
- ▪length of each element.

"power factor" :
type of TE material

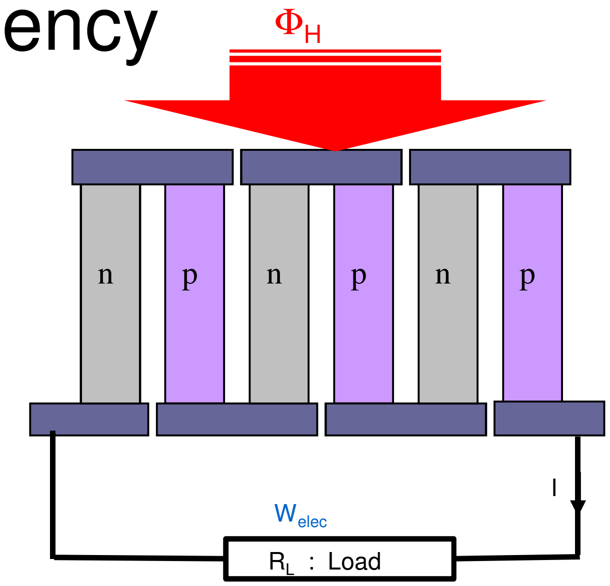
The thermal conductivity, λ, does not appear and so does not directly impact the maximum power.

TE Generator

thermal resistances connecting the thermocouples to the thermal reservoirs

λ impacts ΔT across the thermocouples.

Maximizing Efficiency



The input power is the heat entering the hot junction

$$\Phi_H = N\alpha_{pn}\times I\times Th - \frac{R\times I^2}{2} + K\times\Delta T$$

The output power is the electrical energy

$$Welec = R_L.I^2 = \frac{R_L}{(R+R_L)^2}N^2.\alpha^2.\Delta T^2$$

Efficiency

$$\eta = \frac{Welec}{\Phi_H} = \frac{\frac{R_L}{(R+R_L)^2}N^2.\alpha^2.\Delta T^2}{N.\alpha_{pn}\times I\times Th - \frac{R\times I^2}{2} + K\times\Delta T}$$

After some calculations and by defining $m = \frac{R_L}{R}$

$$\eta = \frac{Welec}{\Phi_H} = \frac{\Delta T}{Th}.\frac{\frac{m}{m+1}}{1+\frac{KR(m+1)}{N^2.\alpha^2 Th} - \frac{\Delta T}{2Th.(m+1)}}$$

Carnot efficiency

by defining $z = \frac{N^2.\alpha^2}{K.R} = \frac{\alpha^2}{4\rho_{pn}.\lambda_{pn}} = \frac{\alpha^2}{\rho.\lambda} = \frac{\sigma.\alpha^2}{\lambda}$ Figure of merit

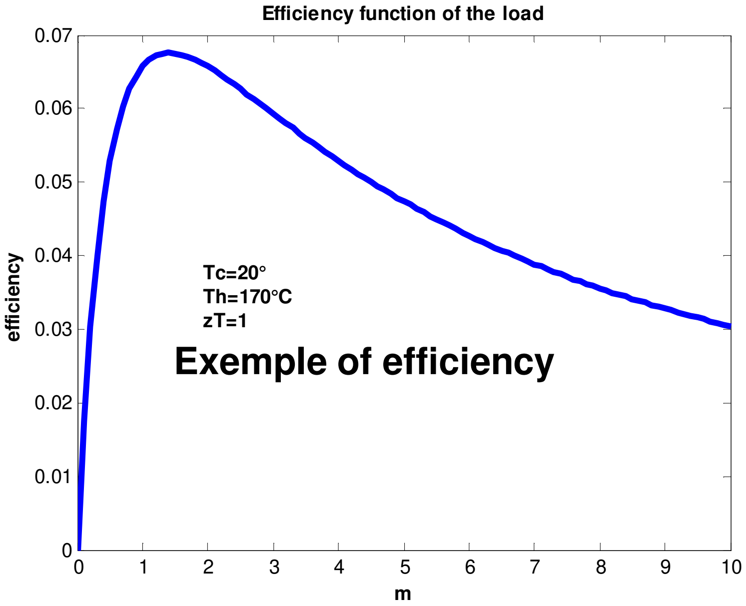
$\rho = \rho_{n+}\rho_p = 2\rho_{pn}$ $\lambda = \lambda_{n+}\lambda_p$ $\alpha = \alpha_p - \alpha_n$

The efficiency becomes

$$\eta = \frac{\Delta T}{Th}.\frac{\frac{m}{m+1}}{1+\frac{(m+1)}{ZTh} - \frac{\Delta T}{2Th.(m+1)}}$$

Efficiency for different electrical loads

Efficiency $$\eta = \frac{Welec}{\Phi_H} = \frac{\Delta T}{Th} \cdot \frac{\frac{m}{m+1}}{1 + \frac{(m+1)}{ZTh} - \frac{\Delta T}{2Th.(m+1)}}$$



Exemple of efficiency

There is a maximum for m≈1.4

The load must be adapted

m can be chosen to maximize the efficiency

$$\frac{\partial \eta}{\partial m} = \frac{\Delta T}{Th} \cdot \frac{2(2m^2 - 2zTh - 2 + \Delta Tz)Th.z}{(-2zThm - 2zTh - 2m^2 - 4m - 2 + \Delta Tz)^2}$$

$$\frac{\partial \eta}{\partial m} = 0 \rightarrow 2m^2 - 2zTh - 2 + \Delta Tz = 0$$

$$m_{opt} = \frac{\sqrt{2zTh + 2zTc + 4}}{2} = \sqrt{z\frac{(Th+Tc)}{2} + 1}$$

$$m_{opt} = \sqrt{1 + zT}$$

Where T is the average temperature $T = \frac{(Th+Tc)}{2}$

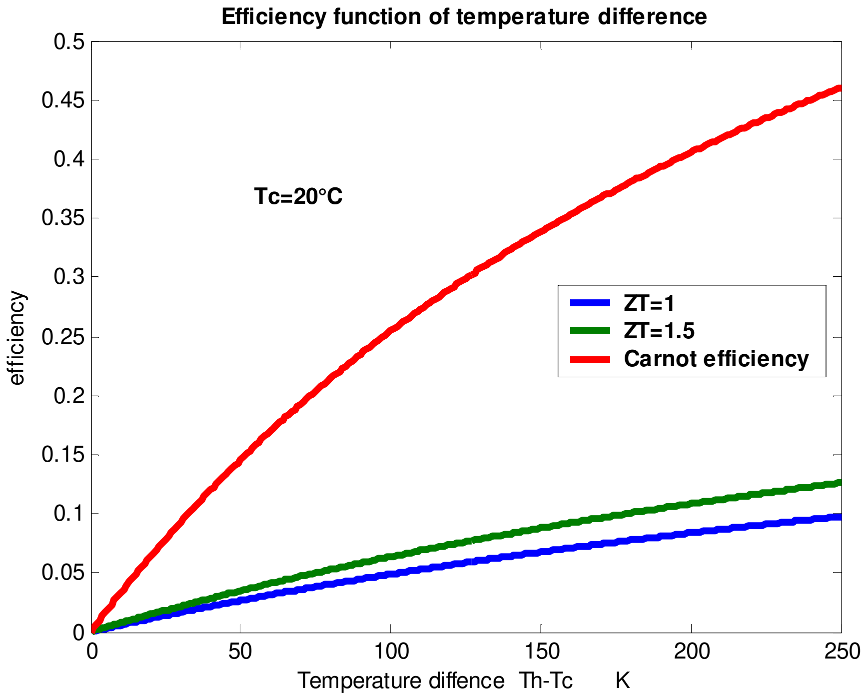
$$\boxed{\eta_{opt} = \frac{\Delta T}{Th} \cdot \frac{\sqrt{1+zT} - 1}{\sqrt{1+zT} + \frac{Tc}{Th}}}$$

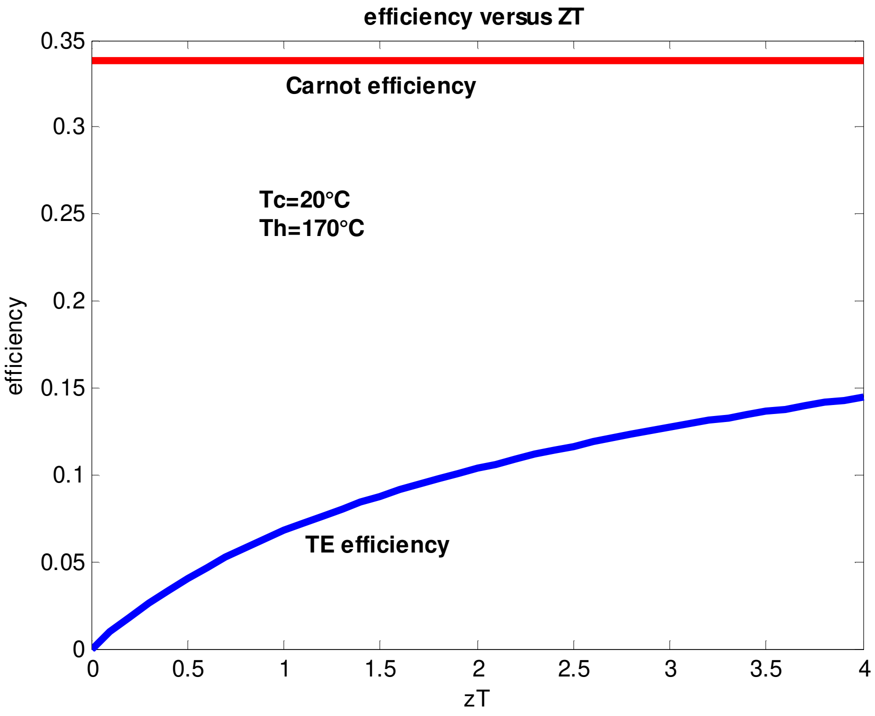
Maximum of efficiency is a function of zT

(Dimensionless figure of merit)

$$z = \frac{\alpha^2}{\rho\lambda} = \frac{\sigma.\alpha^2}{\lambda} \qquad T = \frac{(Th+Tc)}{2}$$

Maximum Efficiency



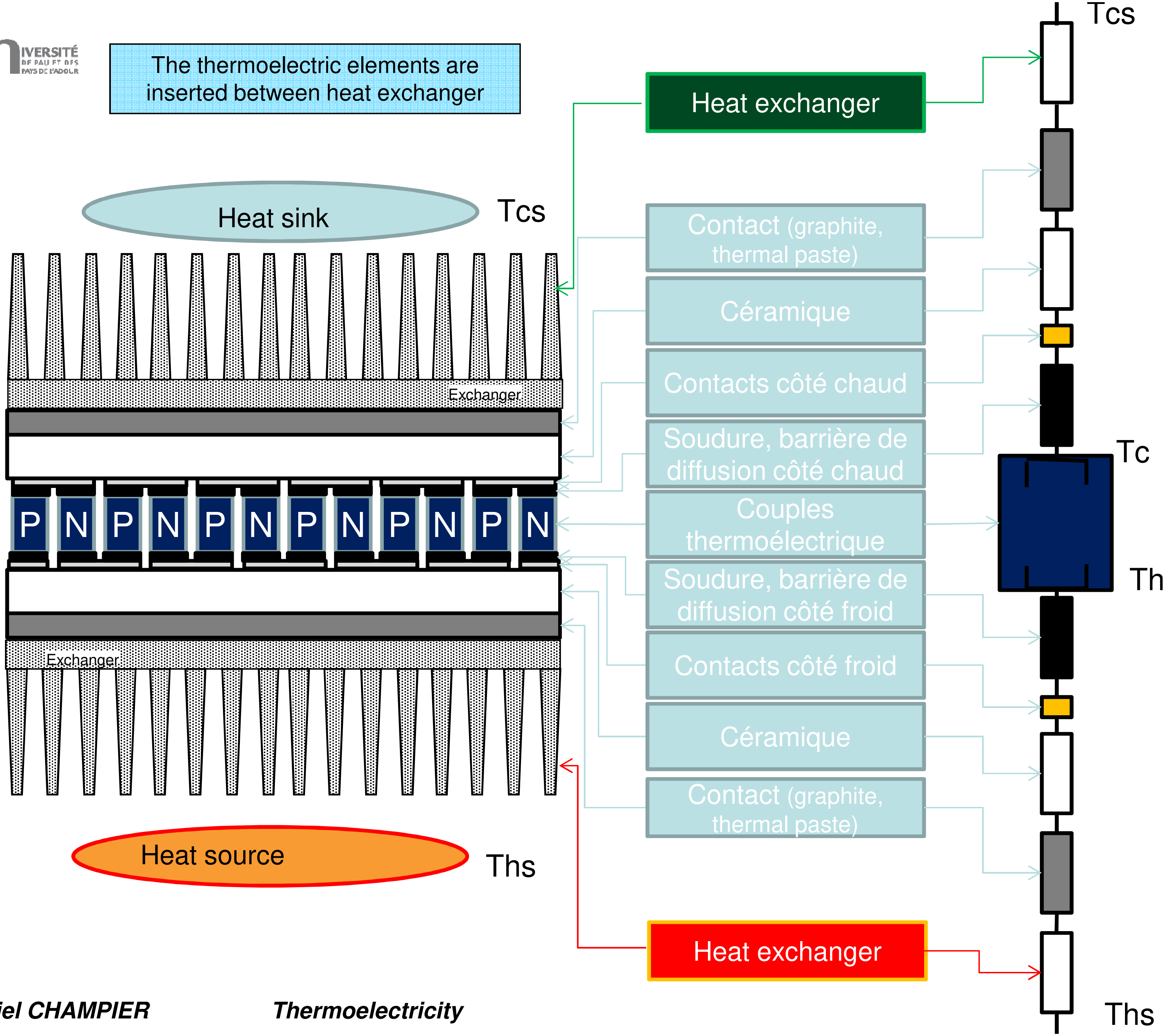


Complete generator model

From heat sources to electrical storage including electrical converters

1) **Adding the heat exchangers to hot and cold sources**
2) **Electrical converters**

The thermoelectric elements are inserted between heat exchanger



Heat exchanger

Contact (graphite, thermal paste)

Céramique

Contacts côté chaud

Soudure, barrière de diffusion côté chaud

Couples thermoélectrique

Soudure, barrière de diffusion côté froid

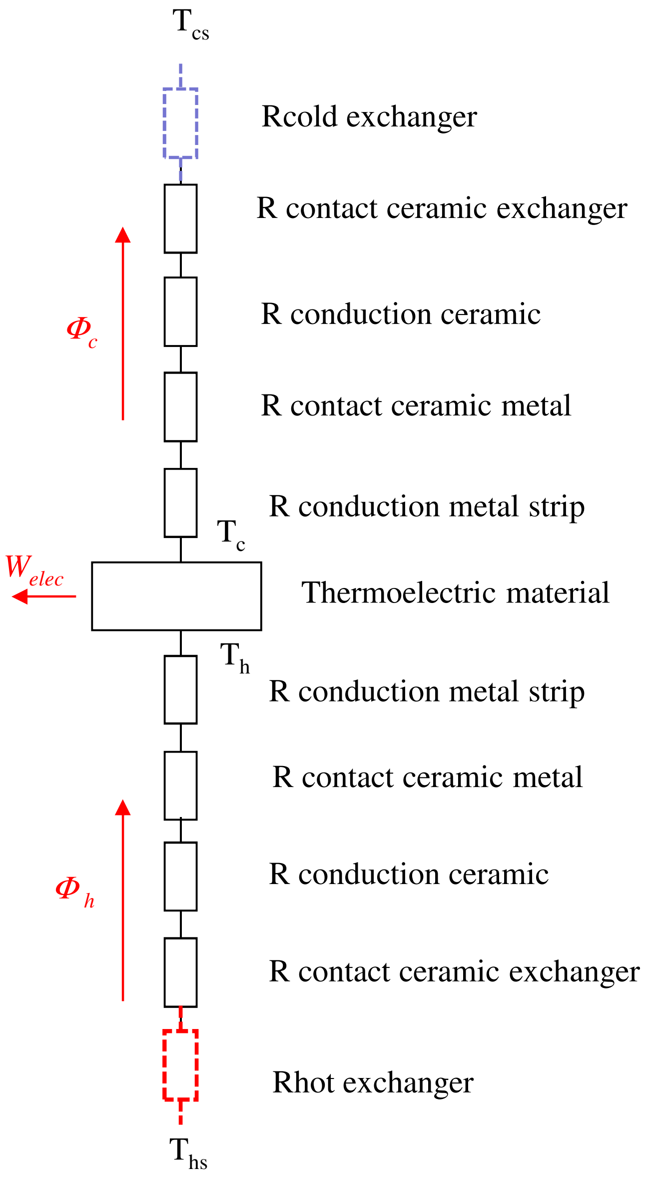
Contacts côté froid

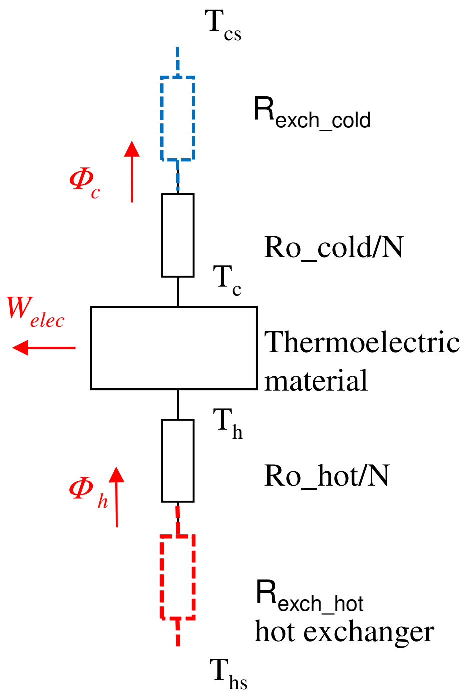
Céramique

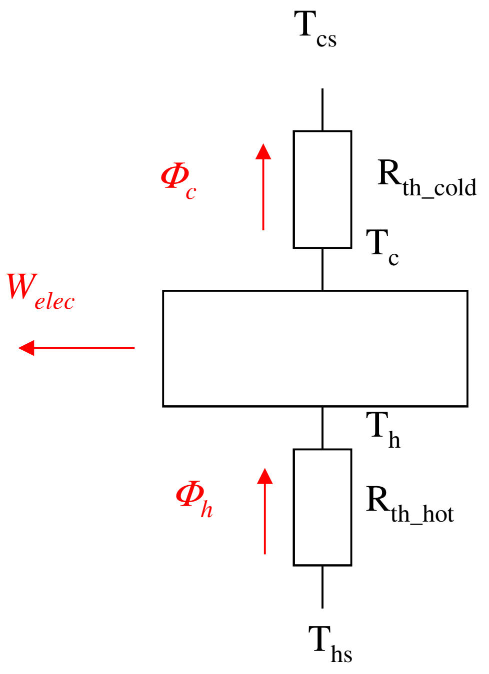
Contact (graphite, thermal paste)

Heat exchanger

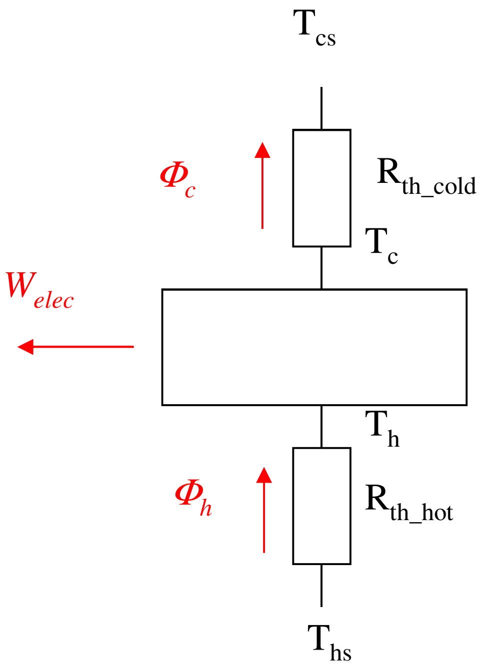
The TE module is inserted between two heat exchangers







Thermoelectric Equations



$$\Phi_h = N.\left[\alpha.I.Th - \frac{1}{2}R_{e\_pn}.I^2 + \frac{(Th - Tc)}{R_{th\_pn}}\right] \qquad (1)$$

$$\Phi_c = N.\left[\alpha.I.Tc + \frac{1}{2}R_{e\_pn}.I^2 + \frac{(Th - Tc)}{R_{th\_pn}}\right] \qquad (2)$$

$$W_{elec} = N.\alpha.I \times (Th - Tc) - N.R_{e\_pn}.I^2 \qquad (3)$$

Thermal Equations

$$\Phi_h = \frac{(Ths - Th)}{R_{th\_hot}} \qquad (4)$$

$$\Phi c = \frac{(Tc - Tcs)}{R_{th\_cold}} \qquad (5)$$

R_{e_pn} Electrical resistance of a couple including contact resistance

R_{th_pn} Thermal resistance of a couple excluding contact resistance

$$\Phi_h = N.\left[\alpha.I.Th - \frac{1}{2}R_{e\_pn}.I^2 + \frac{(Th - Tc)}{R_{th\_pn}}\right] = \frac{(Ths - Th)}{R_{th\_hot}} \qquad (1)\ \&\ (4)$$

$$\Phi c = N.\left[\alpha.I.Tc + \frac{1}{2}R_{e\_pn}.I^2 + \frac{(Th - Tc)}{R_{th\_pn}}\right] = \frac{(Tc - Tcs)}{R_{th\_cold}} \qquad (2)\ \&\ (5)$$

These two equations can be rewritten in matrix form

$$\begin{pmatrix} N.\alpha.I + \dfrac{1}{R_{th\_hot}} + \dfrac{N}{R_{th\_pn}} & -\dfrac{N}{R_{th\_pn}} \\ \dfrac{N}{R_{th\_pn}} & N.\alpha.I - \dfrac{1}{R_{th\_cold}} - \dfrac{N}{R_{th\_pn}} \end{pmatrix} \begin{pmatrix} Th \\ Tc \end{pmatrix} = \begin{pmatrix} \dfrac{Ths}{R_{th\_hot}} + \dfrac{1}{2}N.R_{e\_pn}.I^2 \\ -\dfrac{Tcs}{R_{th\_cold}} - \dfrac{1}{2}N.R_{e\_pn}.I^2 \end{pmatrix}$$

Cramer's rule give an explicit formula for the solution of this system of linear equations

Then you can calculate the electrical output power

$$W_{elec} = N.\alpha.I \times (Th - Tc) - N.R_{e\_pn}.I^2$$

Annex Cramer’s rule

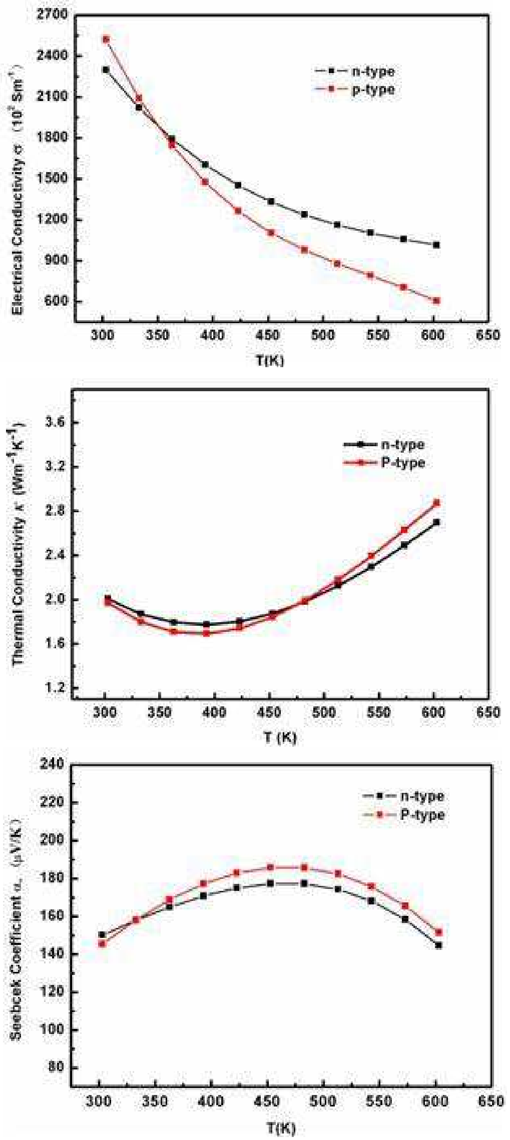
Cramer's rule

$$\begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

$$x = \frac{\begin{vmatrix} c_1 & b_1 \\ c_2 & b_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{c_1 b_2 - c_2 b_1}{a_1 b_2 - a_2 b_1}$$

$$y = \frac{\begin{vmatrix} a_1 & c_1 \\ a_2 & c_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{a_1 c_2 - a_2 c_1}{a_1 b_2 - a_2 b_1}$$

Which values for the material properties ?



λ, ρ, α as function of the temperature for Thermonamics Ingots

Assumptions for the calculations :
The material properties are temperature independent

The equations give good results if one chooses the value at the average temperature.

$$T_{av} = T_m = \frac{T_h + T_c}{2}$$

$$\lambda = \lambda(T_{av})$$
$$\rho = \rho(T_{av})$$
$$\alpha = \alpha(T_{av})$$

But $$\frac{T_h + T_c}{2} \neq \frac{T_{hs} + T_{cs}}{2}$$

you have to do some iterations to find Tm

$T_m(0) = \frac{T_{hs} + T_{cs}}{2}$ ⇒ $T_h(0)$ et $T_c(0)$

$T_m(1) = \frac{T_h(0) + T_c(0)}{2}$ ⇒ $T_h(1)$ et $T_c(1)$

you can make these iterations with I=0 because the average temperature won't change a lot with I

Design (and optimization)

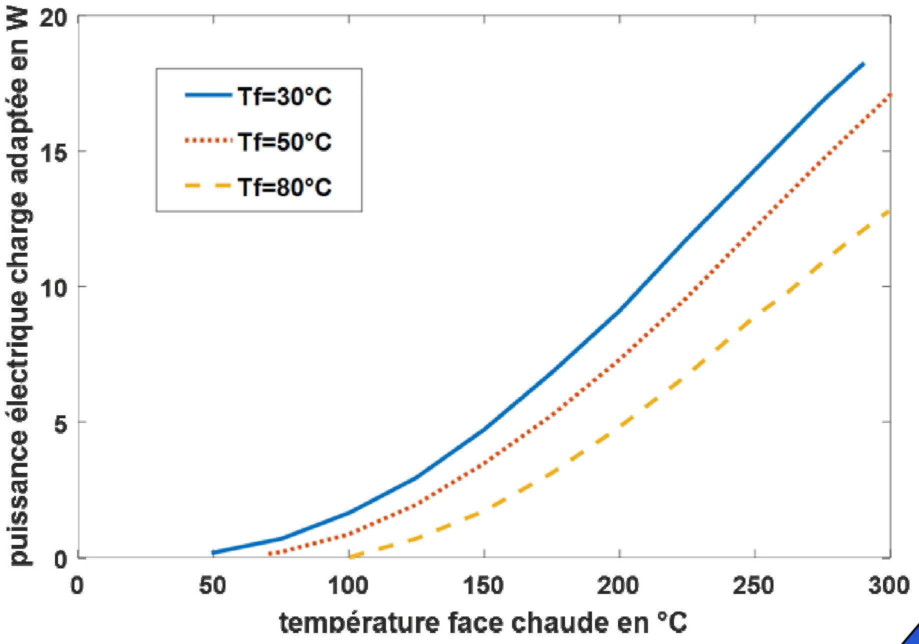
Common error

Consider only the power given in manufacturer's datasheet, for example " 19.2W".

19.2 W is for
- hot side at 300°C
- cold side at 30°C
- adapted electrical load

great disappointment

Hot Side Temperature (℃)	300
Cold Side Temperature (℃)	30
Open Circuit Voltage (V)	7.8
Matched Load Resistance (ohms)	0.8
Matched load output voltage (V)	3.9
Matched load output current (A)	4.9
Matched load output power (W)	19.2
Heat flow across the module(W)	≈400
Heat flow density(Wcm^{-2})	≈12.8



Design (and optimization)

Rough design

- temperatures of the two sources,
- thermal resistance of the exchangers
- thermal resistance of the modules
- No electric current

Calculate the temperature on either side of the modules.

⇨ manufacturer curves gives an idea of the power

power will be overestimated : Joule effect, Peltier effect in the module significantly reduce the temperature difference at the faces of the module

This approach has often been used in the past by automotive integrators and has led to disillusionment with the powers obtained.

Design and optimization

Simplified design

- temperatures of the two sources, Tcs and Ths
- thermal resistance of the exchangers
- knowledge of the properties of materials

I) Calculation of the average temperature for material properties No electric current

1) Choose Tm =average (Tcs,Ths) and calculate Tc(k=0) and Th(k=0) without current

2) Choose Tm =average (Tc(k=0),Th(k=0)) and calculate Tc(k=1) and Th(k=1) without current

3) Iterate on k (normally just a few time)

II) Calculation of the electric output power

1) Calculate the open circuit voltage Eo (rougth estimation of the maximum output power : $\frac{{E_0}^2}{4R}$) I=0

2) Estimate the short circuit current Imax=Eo/R

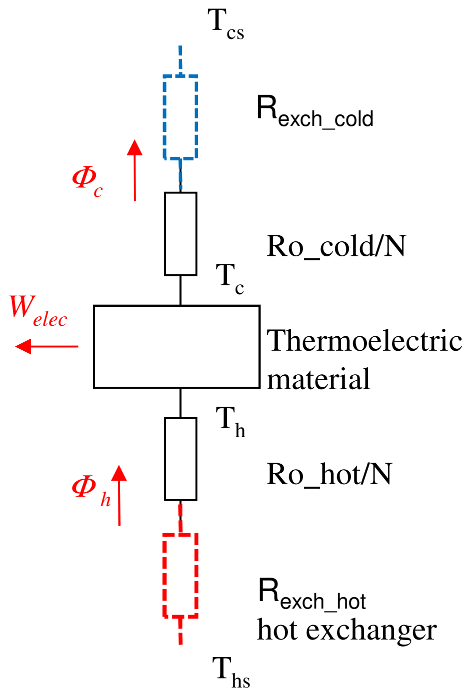
3) Calculate the output power for different values of I, between I=0 and Imax using Kramer's formulas (*possibility to iterate on parameters calculation*)

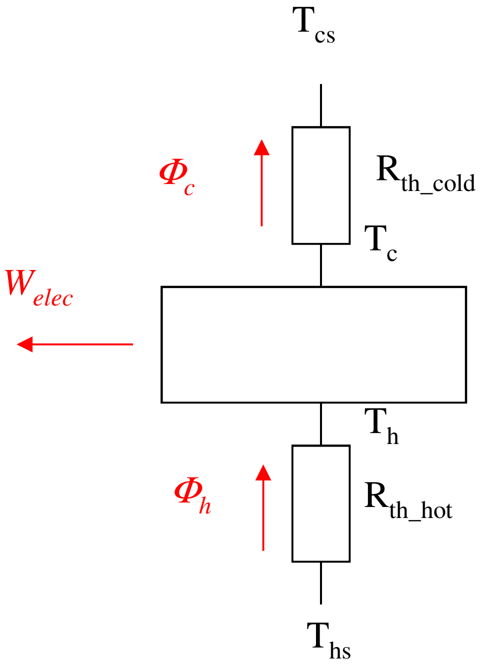
4) Calculate the maximum electrical power.

Example

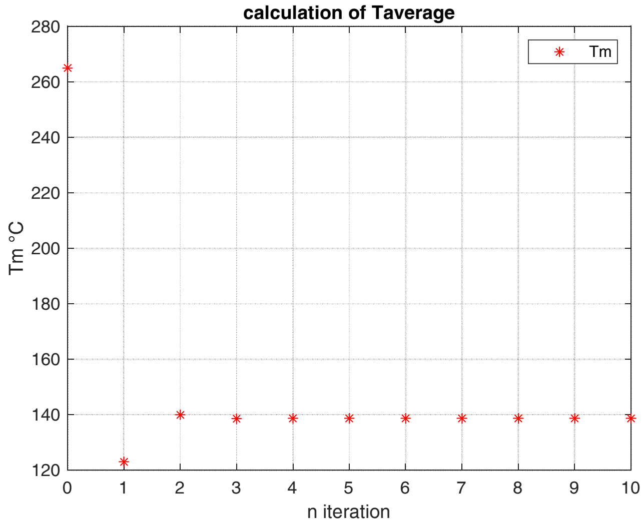
Ths=500°C
Tcs=30 °C

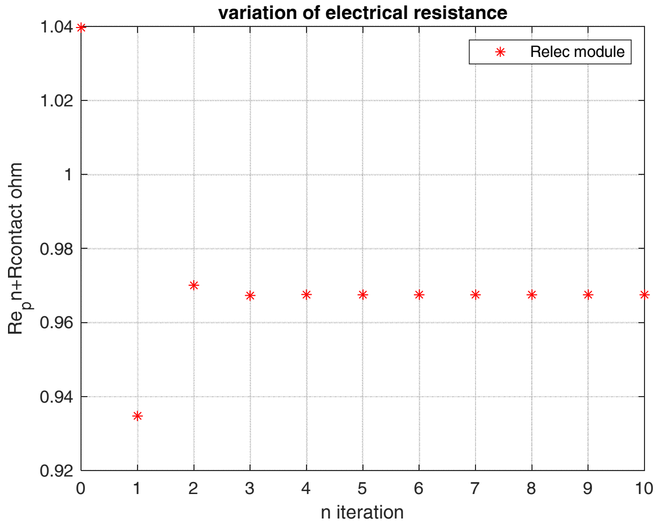
Rexch_hot=1
Rexch_cold=0.05
Ro_cold/N = Ro_hot/N = 0.14K/W
Rth_hot=1.14;
Rth_cold=0.14;
Rcontact=0.30 electric contact resistance for the whole module
Material properties of the previous slide
N=128 couples

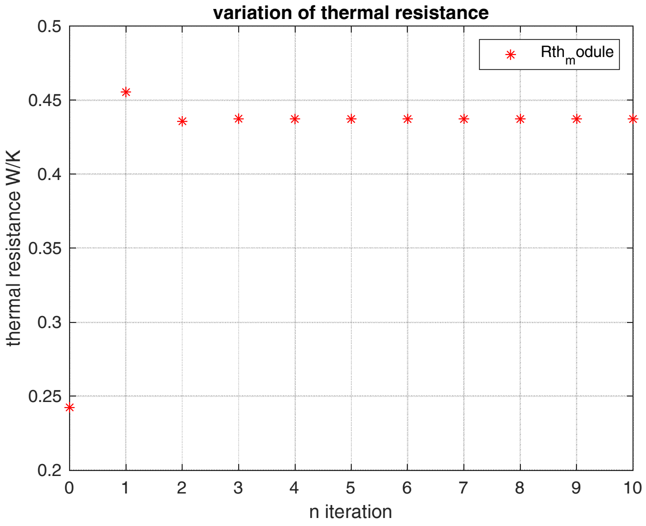


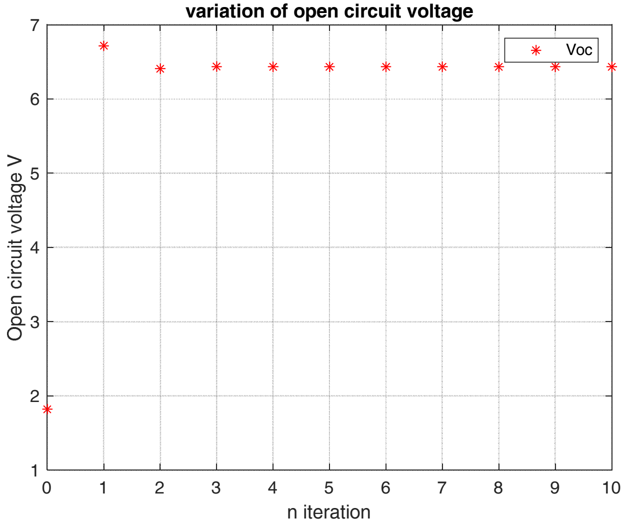


Example : Calculation of the average temperature for material properties

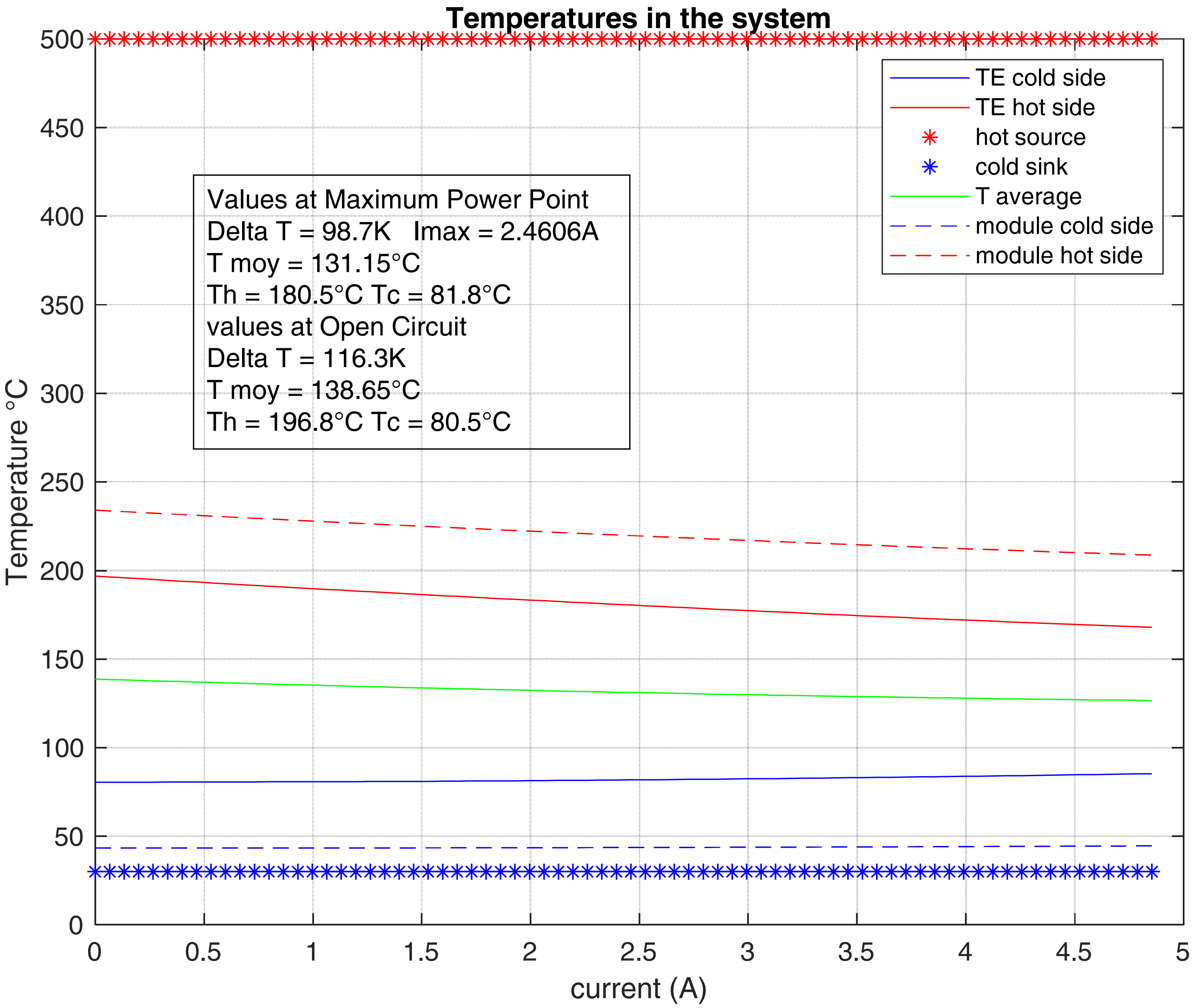

calculation of Taverage


variation of electrical resistance

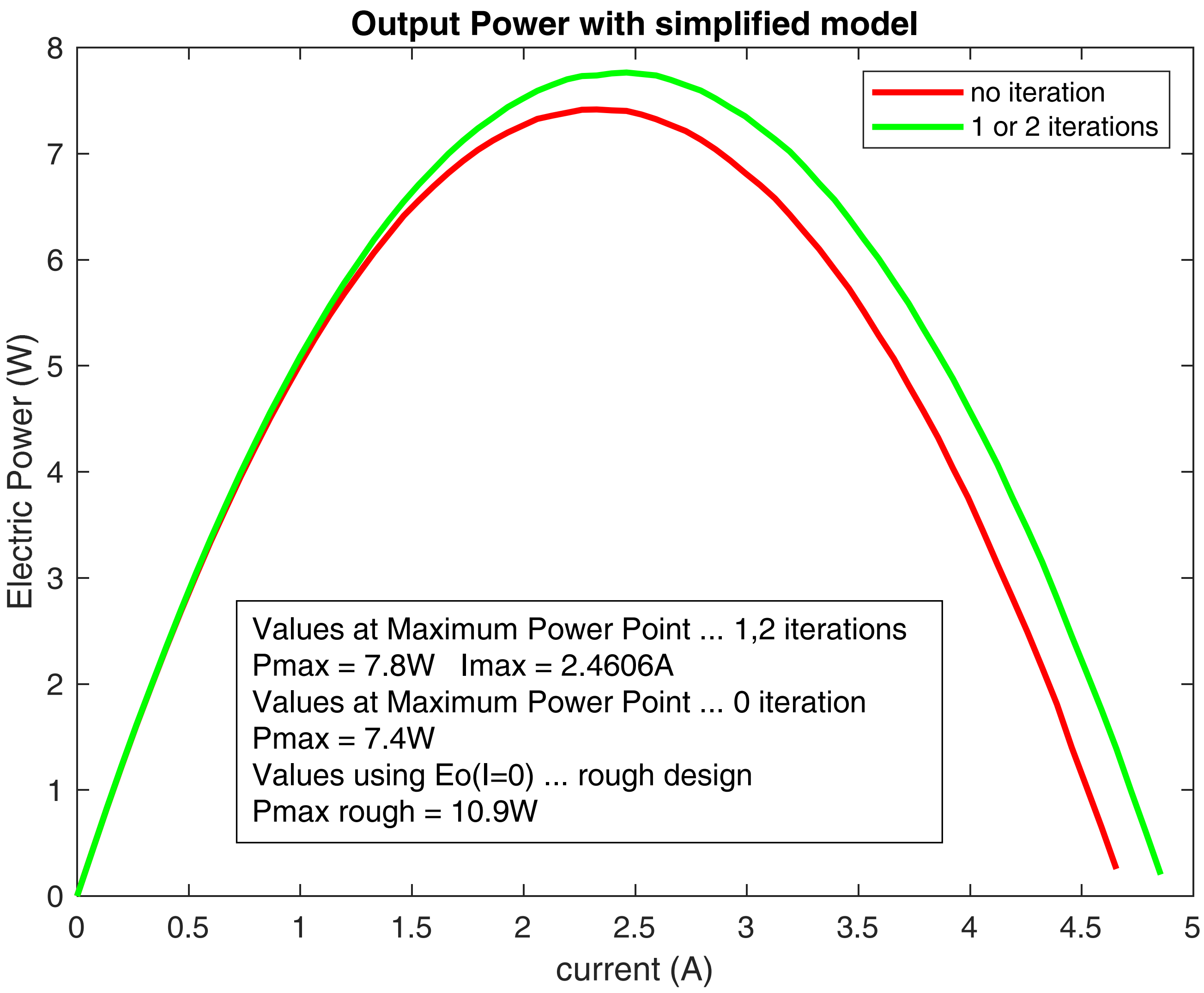

variation of thermal resistance


variation of open circuit voltage

Example : Calculation of the temperatures



Example : Calculation of electrical power


Output Power with simplified model

Values at Maximum Power Point ... 1,2 iterations
Pmax = 7.8W   Imax = 2.4606A
Values at Maximum Power Point ... 0 iteration
Pmax = 7.4W
Values using Eo(I=0) ... rough design
Pmax rough = 10.9W

10.9W   7.4W → 7.8W   is iteration necessary?

Design (and optimization)

Remarks on simplified design

- temperatures of the two sources, Tcs and Ths **Are they spatially constant ?**

If not you must cut in different slides

Are they constant over time ?

If not, you can consider dynamic equations for the thermal part and keep quasi-static equation for the TE parts

- thermal resistance of the exchangers **high uncertainty on convective heat exchange coefficients … difficult part of the job**

- knowledge of the properties of materials

Some manufacturers give these properties (HiZ, Thermonamic)

Most manufacturers give only: electrical resistance and maximum output power as a function of temperatures but up to now they don't give the thermal conductance of their modules.

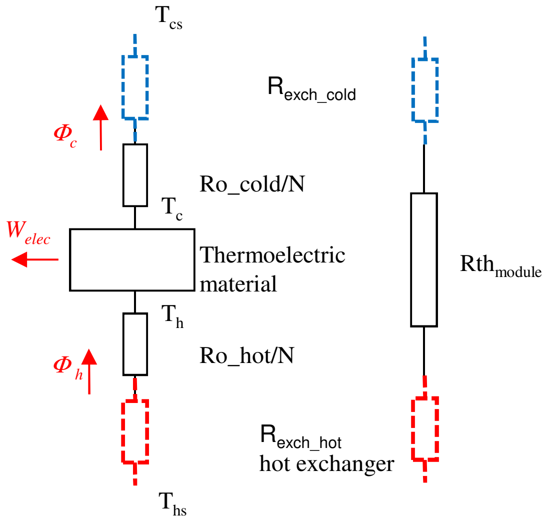
You need to estimated it by your own measurements (Manufacturers started to develop bench measuring Seebeck, Electrical Resistance and Thermal Resistance)

Optimization : Maximizing power output from a generator

$$W_{elec}^{Max} = \Delta T^2 \, . \, \frac{NS}{8L} \, . \, \sigma_{pn} \alpha^2 = \boxed{\Delta T^2} \, \boxed{N} \, . \frac{S}{8L} \sigma_{pn} \alpha^2$$

How many modules to put on? More elegantly how much couple to put in?

Optimization : Maximizing power output from a generator



Thermal resistance of N couples $R_{th\_N\_couples} = \frac{L}{2 \cdot \lambda_{np} . S} \cdot \frac{1}{N} = R_{th\_pn} \cdot \frac{1}{N}$

Thermal contact + resistance ceramic strip for each couple $R_o = R_o\_cold + R_o\_hot$

If you neglect the Thermoelectric effect (Peltier and Joule) :

Thermal resistance of a module $R_{th_{module}} = R_{th\_N\_couples} + \frac{Ro}{N} = (R_{th\_pn} + Ro) . \frac{1}{N}$

Calculating the temperature difference between the two side of the thermoelectric materials

$$\Delta T = \frac{R_{th\_N\_couples}}{R_{th_{module}} + R_{exch\_cold} + \mathbf{R}_{exch\_hot}} \left(T_{hs} - T_{cs}\right) = \frac{R_{th\_N\_couples}}{R_{th_{module}} + \mathbf{R}_{exc}} \left(T_{hs} - T_{cs}\right) = \frac{R_{th\_pn} \cdot \frac{1}{N}}{(R_{th\_pn} + Ro) . \frac{1}{N} + \mathbf{R}_{exc}} \left(T_{hs} - T_{cs}\right) = \frac{\frac{R_{th\_pn}}{\mathbf{R}_{exc}}}{\frac{(R_{th\_pn} + Ro)}{\mathbf{R}_{exc}} + N} \left(T_{hs} - T_{cs}\right)$$

$$W_{elec}^{Max} = \Delta T^2 \cdot N \cdot \frac{S}{8L} \sigma_{pn} \alpha^2 = \left[\frac{\frac{R_{th\_pn}}{\mathbf{R}_{exc}}}{\frac{(R_{th\_pn} + Ro)}{\mathbf{R}_{exc}} + N} \left(T_{hs} - T_{cs}\right) \right]^2 N \cdot \frac{S}{8L} \sigma_{pn} \alpha^2 = \frac{N}{\left(\frac{(R_{th\_pn} + Ro)}{\mathbf{R}_{exc}} + N \right)^2} \left[\frac{R_{th\_pn}}{\mathbf{R}_{exc}} \left(T_{hs} - T_{cs}\right) \right]^2 \cdot \frac{S}{8L} \sigma_{pn} \alpha^2$$

Optimization : Maximizing power output from a generator

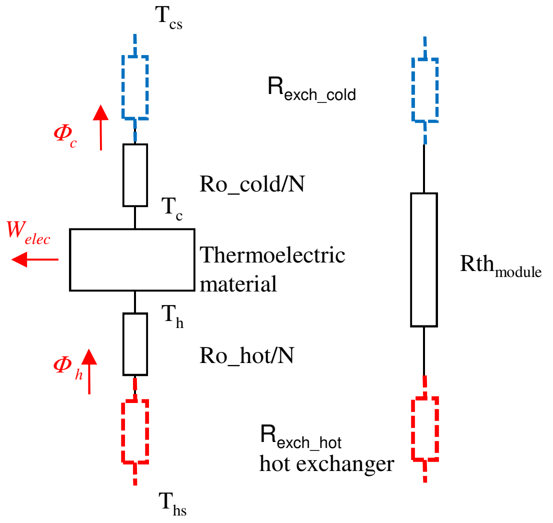
$$W_{elec}^{Max} = \frac{N}{\left(\frac{(R_{th\_pn}+Ro)}{R_{exc}}+N\right)^2}\left[\frac{R_{th\_pn}}{R_{exc}}(T_{hs}-T_{cs})\right]^2 \cdot \frac{S}{8L}\ \sigma_{pn}\alpha^2$$

Maximizing the electrical Power :

$$\frac{\partial W_{elec}^{Max}}{\partial N}=0 \qquad \frac{\partial W_{elec}^{Max}}{\partial N} = \frac{\frac{(R_{th\_pn}+Ro)}{R_{exc}}-N}{\left(\frac{(R_{th\_pn}+Ro)}{R_{exc}}+N\right)^3}\left(\frac{R_{th\_pn}}{R_{exc}}\right)^2 (T_{hs}-T_{cs})^2 \cdot \frac{S}{8L}\ \sigma_{pn}\alpha^2 \Longrightarrow N = \frac{(R_{th\_pn}+Ro)}{R_{exc}}$$

$$Rth_{module} = \frac{(R_{th\_pn}+Ro)}{N} = R_{exc}$$

Thermal impedances matching



The temperature difference of the 2 sides of the module is half of the temperature difference between sources.

Rule of thumb

Strong assumptions : thermoelectric parameters do not depend on temperature
neglecting thermoelectric effect.

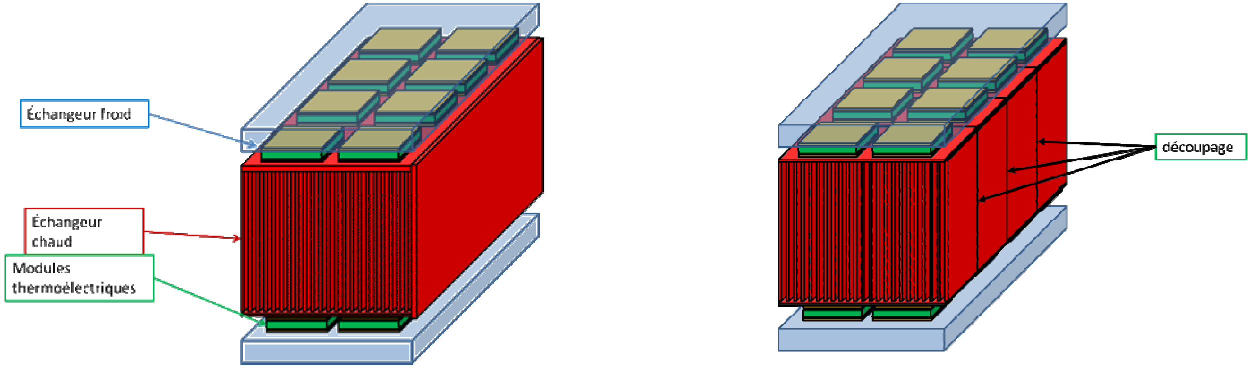
$$W_{elec}^{Max} == \left(\frac{R_{th\_N\_couples}}{Rth_{module}}\right)^2 \left(\frac{T_{hs}-T_{cs}}{2}\right)^2 \cdot \frac{NS}{8.L}\sigma_{pn}\alpha^2$$

Be careful, this relation overestimated the power, because again the temperature difference is calculated by neglecting Peltier and Joule effect.

Design and optimization

Complexe design

In the case of non-ideal heat sources (e. g. hot gas cooling along an exchanger), the approach will be to use the TE equations and Thermal equations coupled with fluid dynamics equations.



optimization

Many parameters can be optimized, number of modules, heat exchanger, materials, geometry of modules

Heavy calculations → genetic algorithms

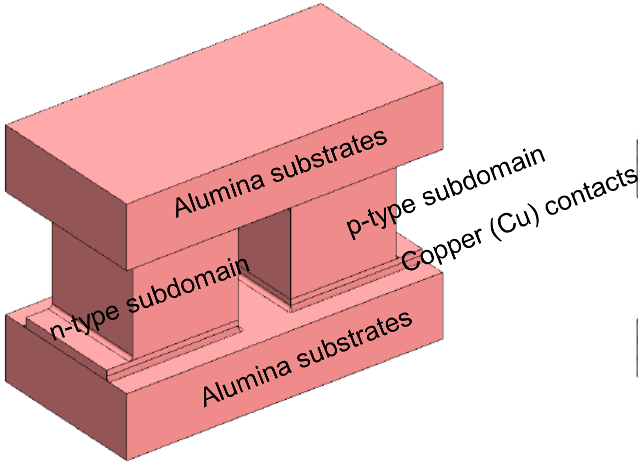
Finite Element Models

a FE model can provide several unique advantages.

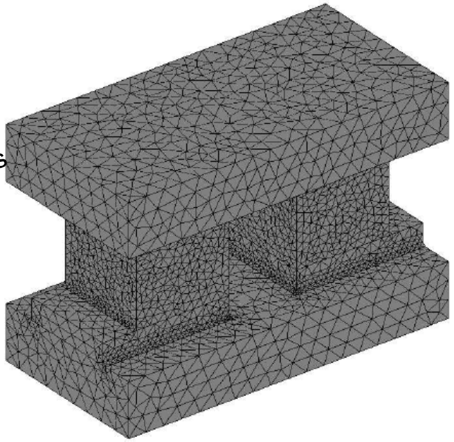
It can solve the governing set of partial differential equations that cannot be solved analytically.

It permits the investigation of complex geometries.

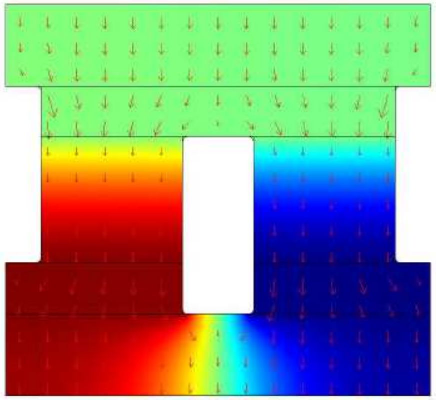
The non-linearities of the material property temperature-dependency can be handled, whereas an analytical solution does not exist.



FEA model of a thermoelement junction in COMSOL



Final COMSOL mesh



The voltage gradient is seen in color the arrows indicate heat flow

The analysis of hundred of thermoelements pairs is **highly computationally** intensive

The model are limited to a few pairs

Finite Element Software Package : Comsol, Ansys Fluant, etc

Emil Jose Sandoz-Rosado, Thesis, Improved Modeling of a Thermoelectric Module

Thermoelectric equations : other models

Standard simplified model

$$\Phi_h = \alpha \times I \times Th - \frac{r \times I^2}{2} + k \times (Th - Tc)$$

All parameter evaluated at $Tm = \frac{Th + Tc}{2}$

$$\Phi_c = \alpha \times I \times Tc + \frac{r \times I^2}{2} + k \times (Th - Tc)$$

$$W_{elec} = \alpha \times I \times (Th - Tc) - r \times I^2$$

Thomson simplified model

$$\Phi_h = \alpha \times I \times Th - \frac{r \times I^2}{2} + k \times (Th - Tc) - \frac{1}{2} \tau \times I \times (Th - Tc)$$

Introducing Thomson' coefficient $\tau = T \times \left.\frac{\partial \alpha(T)}{\partial \alpha}\right|_{Tm}$

$$\Phi_c = \alpha \times I \times Tc + \frac{r \times I^2}{2} + k \times (Th - Tc) + \frac{1}{2} \tau \times I \times (Th - Tc)$$

$$W_{elec} = (\alpha - \tau) \times I \times (Th - Tc) - r \times I^2$$

Thomson Seebeck simplified model

Seebeck' surface coefficients

$$\Phi_h = \alpha(Th) \times I \times Th - \frac{r \times I^2}{2} + k \times (Th - Tc) - \frac{1}{2} \tau \times I \times (Th - Tc)$$

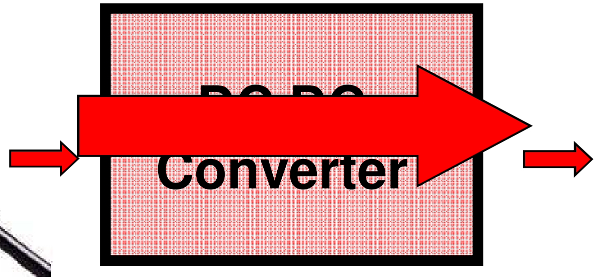
$$\Phi_c = \alpha(Tc) \times I \times Tc + \frac{r \times I^2}{2} + k \times (Th - Tc) + \frac{1}{2} \tau \times I \times (Th - Tc)$$

$$W_{elec} = \left[\alpha(Th) \times Th - \alpha(Tc) \times Tc\right] \times I - r \times I^2 - \tau \times I (Th - Tc)$$

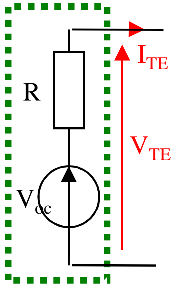
1996 Chen The influence of Thomson effect on the maximum power output and maximum efficiency of a thermoelectric generator

Power convertor

TE modules



$$V_{oc}=N.\alpha\,(T_h-T_c)$$
$$R=R(T_h,T_c)$$



TE Generator

The temperature Th and Tc varies a lot.

output voltage of the TE modules fluctuates a lot.

The loads need regulated voltage

An electric power convertor is necessary

Power convertors for TE generators

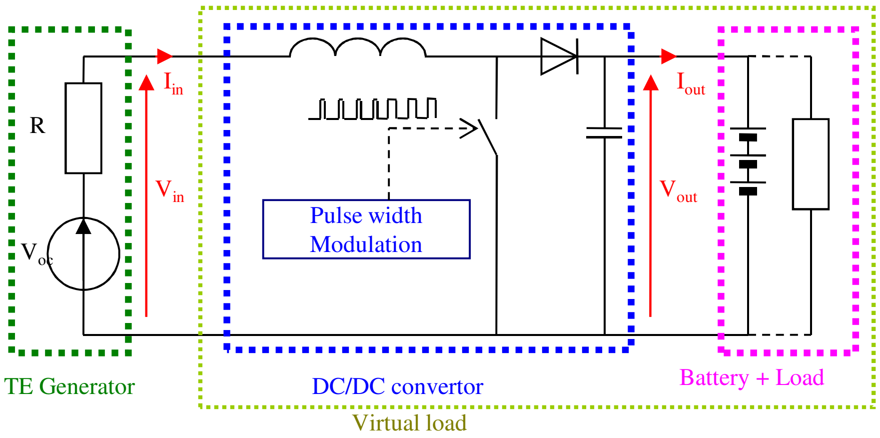
Power convertors convert electric power from one form to another

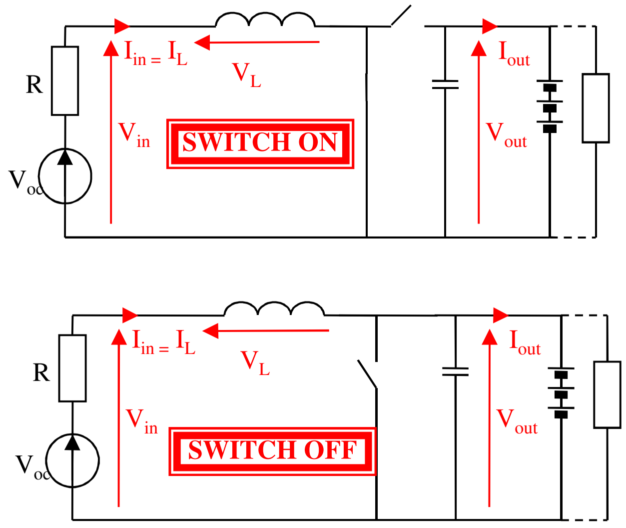
TE modules are direct current (DC) source
Loads are mostly DC (batteries) but possibly alternating current AC (grid connection)

DC – DC
Step-up (Boost) : The storage voltage is higher than the Te modules voltage
Buck-Boost : The storage voltage is higher or lower than the Te modules voltage

DC – AC
Inverter commonly used to supply AC power from DC sources such as solar panels or batteries

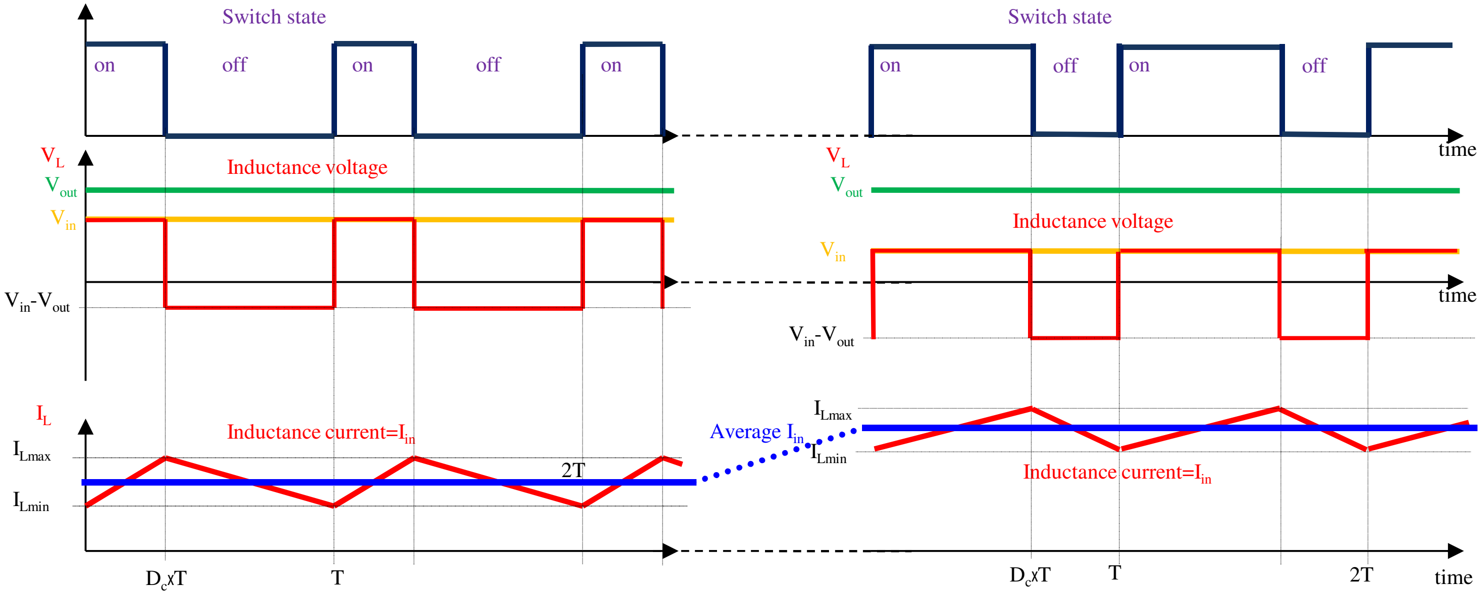
Boost convertor



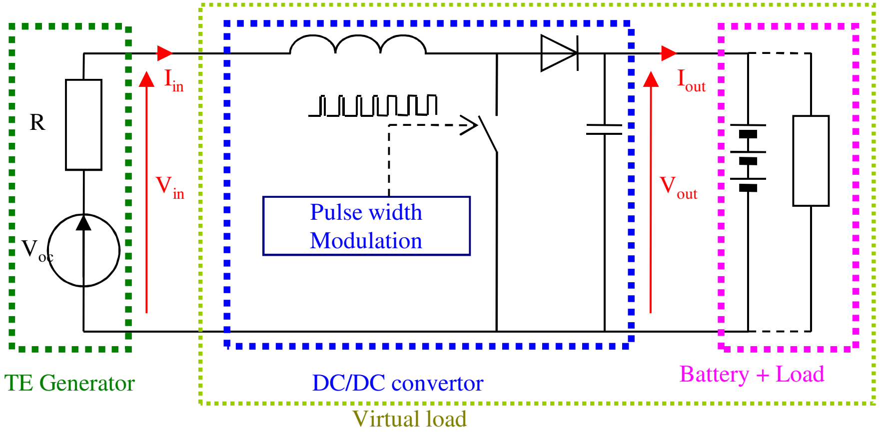


Dc duty cycle :

fraction of the commutation period T during which the switch is On.



Boost convertor



Ideal convertor :

$$\begin{cases} V_{in} = V_{out} \times (1 - Dc) \\ I_{in} = \dfrac{I_{out}}{(1 - Dc)} \end{cases}$$

$$P_{in} = V_{in} \times I_{in} = V_{out} \times I_{out} = P_{out}$$

V_{out} is fixed by the battery voltage

↓

The choice of the duty cycle therefore imposes the voltage Vin and thus the currents

$$I_{in} = \frac{V_{oc} - V_{in}}{R}$$

For an adapted load (maximum power) V_{in} must be equal to $V_{oc}/2$

V_{oc} of the TE modules fluctuates a lot.

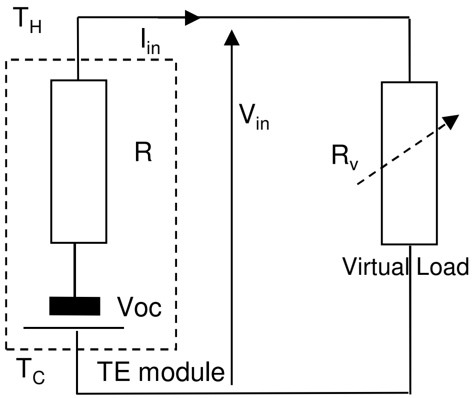
→

The duty cycle needs to follow these variations

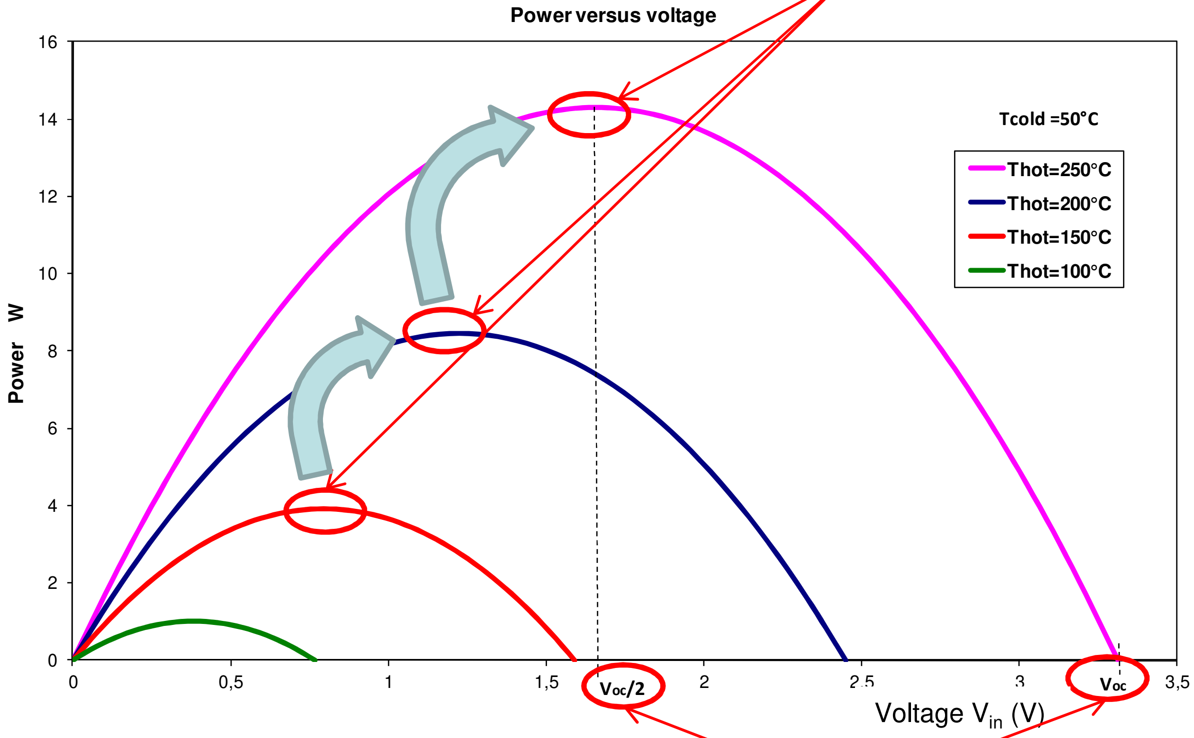
Maximum Power Point (MPP)

Exemple of TE module HiZ 14

Electrical Power



Maximum power point

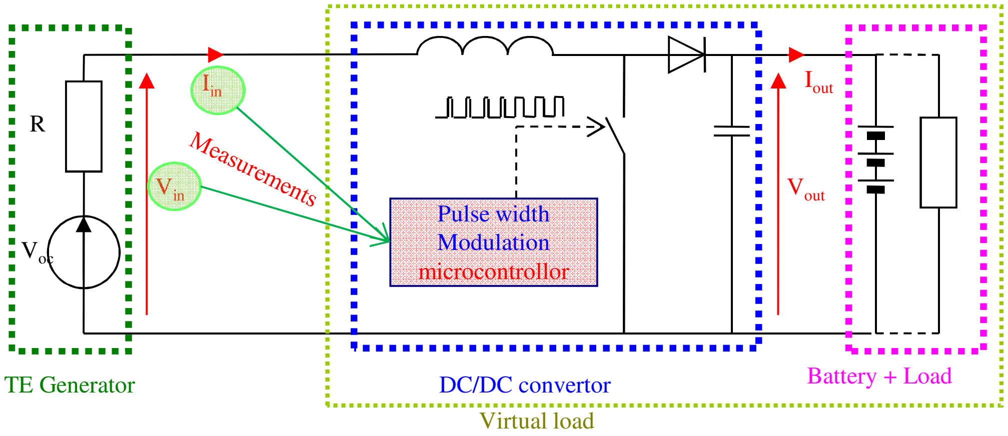


Open circuit voltage
and
adapted voltage

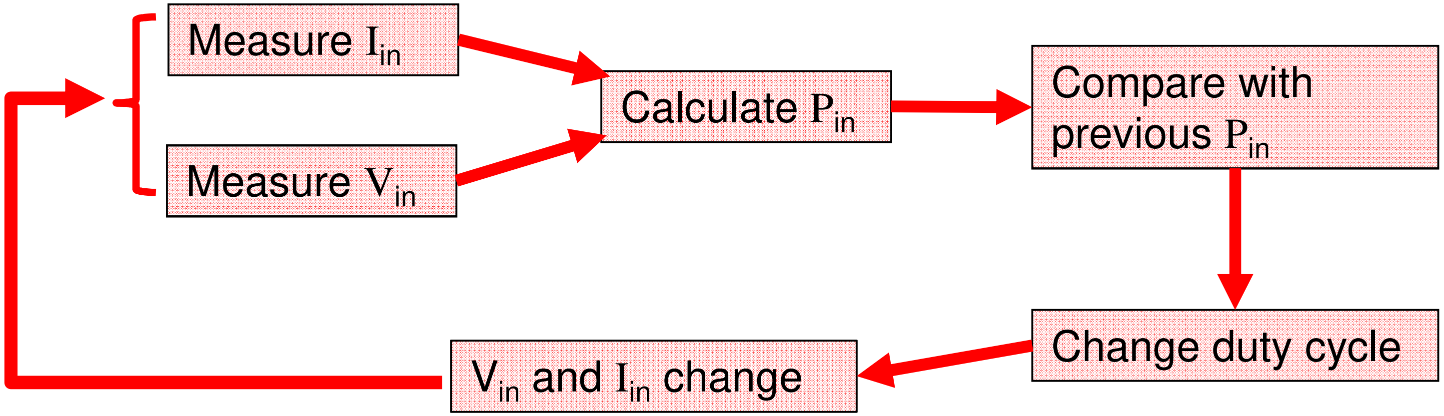
The MMP changes with the temperatures
Intelligence is necessary

Daniel CHAMPIER *Thermoelectricity*

Boost convertor with MPPT



The solution is to control the DC/DC converter with a Maximum Power Point Tracker


Measure I_{in}

Measure V_{in}

Calculate P_{in}

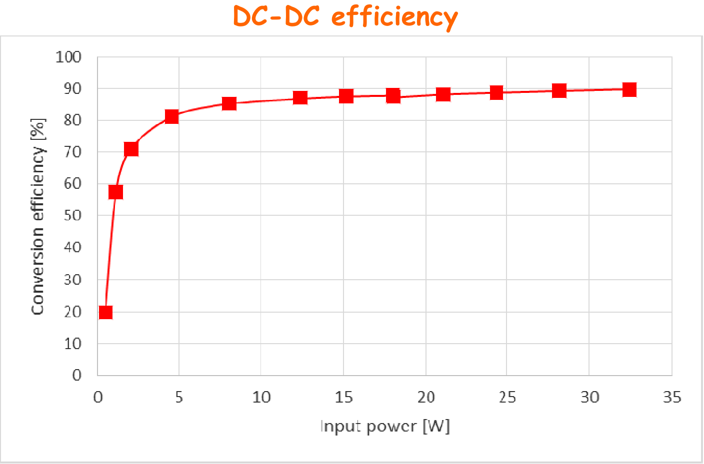
Compare with previous P_{in}

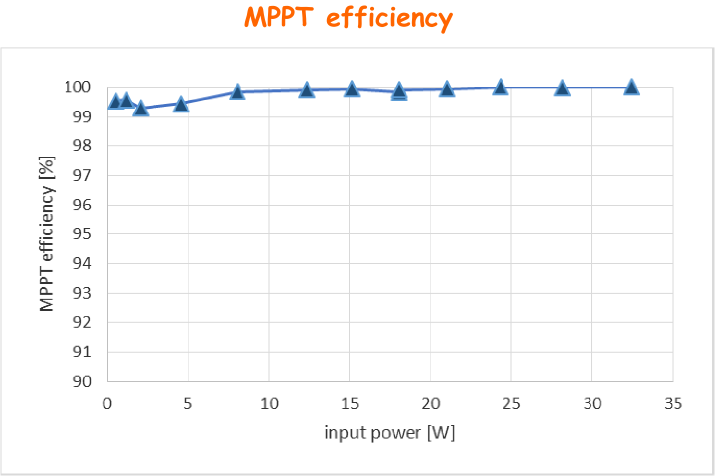
Change duty cycle

V_{in} and I_{in} change

Question : how to change the duty cycle?
Algorithm MPPT

Remarks on electrical part





Optimization of modules (length and area of leg) does not take in account all the components (wires, power convertor, contacts) between modules and end use of the electricity.

Joule effect irreversible and every where

RI^2

Applications

Production in extreme environments
Waste Heat Recovery (WHR)
Domestic production
Microgeneration: sensors, connected objects (IOT)
Thermoelectric solar power

Refrigeration and regulation

Metrology

Electricity production in extreme environment

critical applications:

- **a power source extremely reliable over very long periods.**

- **extreme climatic conditions:**
    - **very hot**
    - **very cold**
    - **very wet**
    - **very dry.**

- **Maintenance as low as possible**
    - **helicopter access**
    - **several hour trip**

- **Maintenance does not exist in the case of space expeditions.**

- **operation in a vacuum**

- **vibrations.**

- **insensitive to radiation**

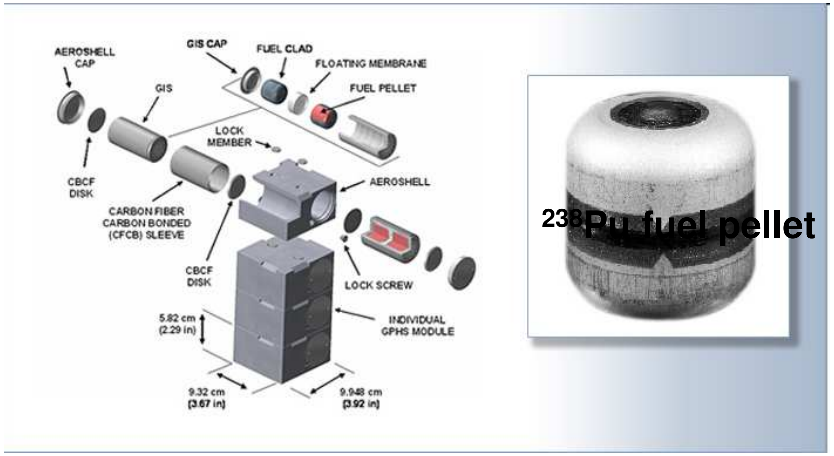
The cost of watt is not essential

Space applications

1961 : First use of a thermoelectric generator (Pb -Te) : navigation satellite Transit
SNAP-3 (Space Nuclear Auxiliary Power)
Electrical power~2,7 watts
worked for more than fifteen years

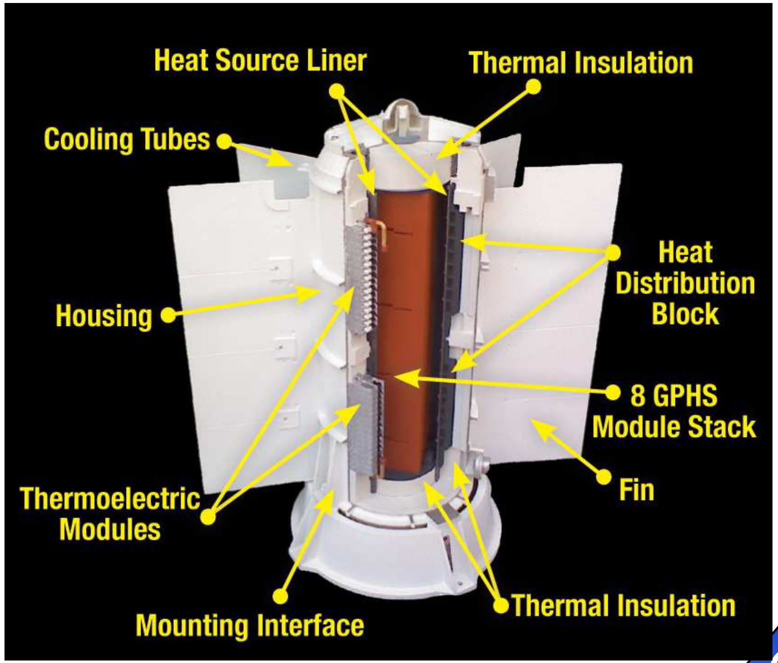
RTG Radioisotope Thermoelectric Generator

Radioisotope Thermoelectric Generators, or RTGs convert the heat generated by the decay of plutonium-238 (plutonium dioxyde $^{238}PuO_2$) fuel into electricity

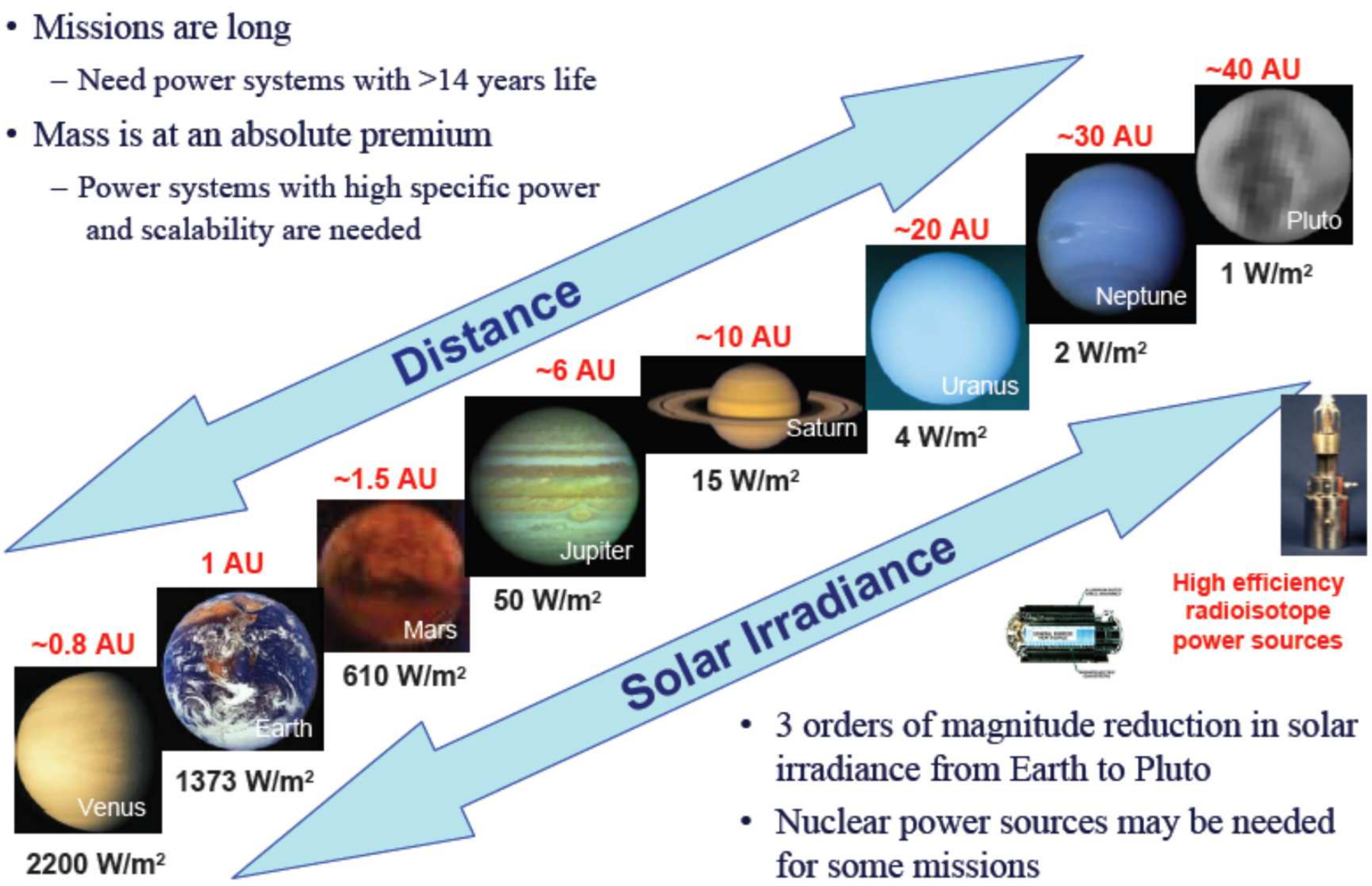


GPHS : General Purpose Heat Source module

http://solarsystem.nasa.gov/rps/rtg.cfm



Space applications

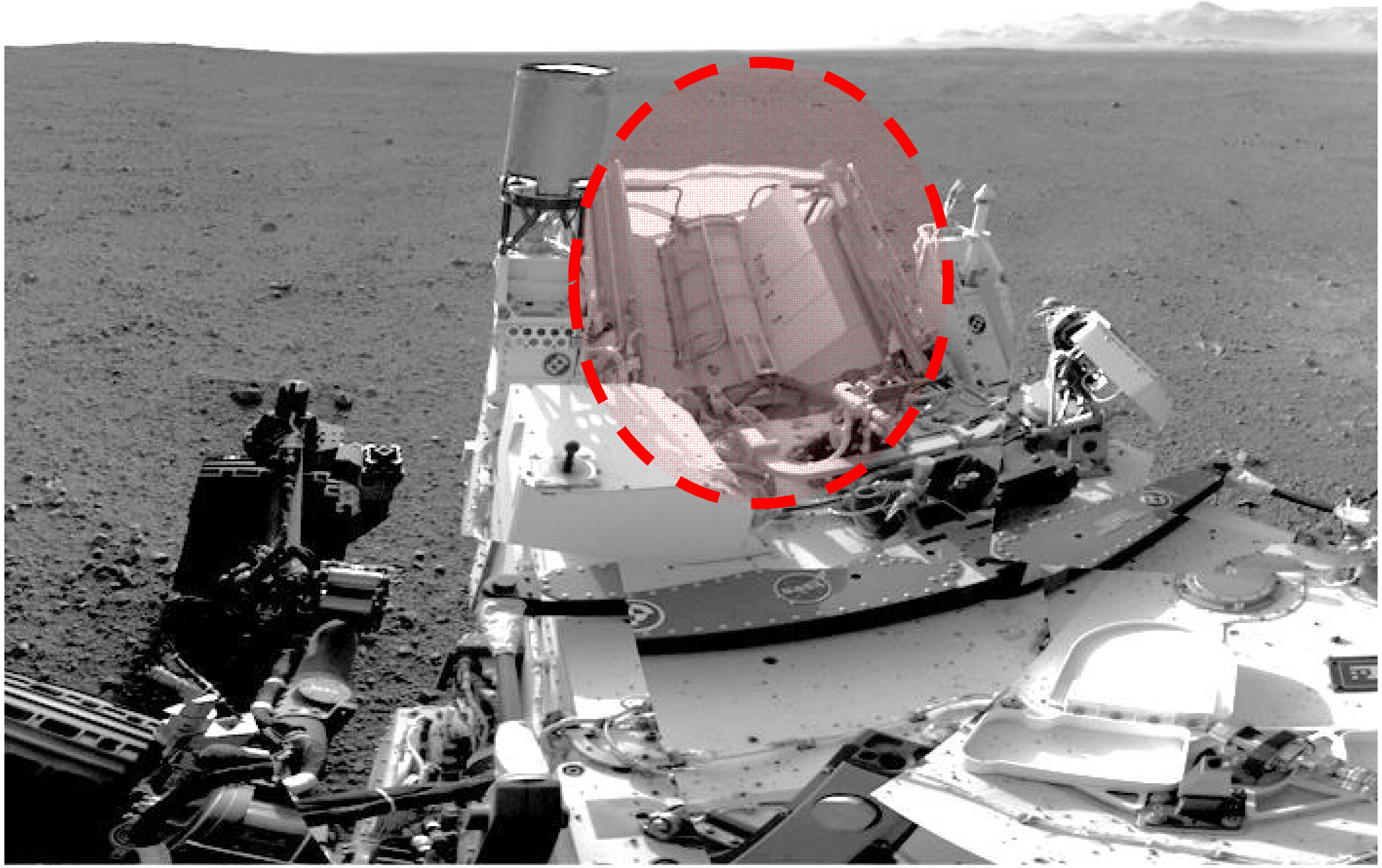


- Missions are long
  - Need power systems with >14 years life
- Mass is at an absolute premium
  - Power systems with high specific power and scalability are needed

- 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Nuclear power sources may be needed for some missions

T. Caillat et al 23rd rd Symposium on Space Nuclear Power and Propulsion STAIF 2006Jet Propulsion Laboratory/California Institute of Technology

Space applications (Mars exploration)



Curiosity 2mx2mx2m
RTG 0.6mx0.6mx0.6
45kg 110W
PbTe Tag

Curiosity's Radioisotope Thermoelectric Generator

http://solarsystem.nasa.gov/rps/rtg.cfm

Space applications

Radioisotope Thermoelectric Generator RTG	Electric Power at beginning of mission per RTG	Number of RTG	Mission	destination	year	design lifetime	lifetime
Space Nuclear Auxiliary Power SNAP-3 PbTe	2,7 Watts	1	Transit	Navigation satellite	1961		15 years
SNAP-19B RTG PbTe-Tags	28.2 Watts	2	Nimbus III	meteorological satellite	1969		
SNAP-19 RTG PbTe-Tags	42.6 Watts	2	Viking 1	Mars landers	1975	90 days	6 years
		2	Viking 2	Mars landers	1975	90 days	4 years
	40.3 Watts	4	Pioneer 10	Jupiter, asteroid belt	1972	5 years	30 years
		4	Pioneer 11	Jupiter Saturn	1973	5 years	22 years
SNAP-27 RTG PbSnTe	70 Watts		Apollo 12, 14, 15, 16 , 17	Lunar Surface	1969-72	2 years	5-8 years
Multi-Hundred Watt (MHW) RTG SiGe	158 Watts	3	Voyager 1 & 2	edge of solar system	1977		still operating over 42 years
General Purpose Heat Source (GPHS) RTG SiGe	292 Watts	2	Galileo	Jupiter	1989		14 years
		3	Cassini	Saturn End mission 2017	1997		21 years
		1	Ulysses	Jupiter	1990		21 years
		1	New Horizons	Pluto (12/2014) , Kuiper Belt (2019)	2006		still operating after 13 years
Multi-Mission Radioisotope Thermoelectric Generator MMRTG PbTe-Tags	110 Watts	1	Curiosity	Mars Surface 5 Aug 2012	2011		Expected 14 years

Space applications

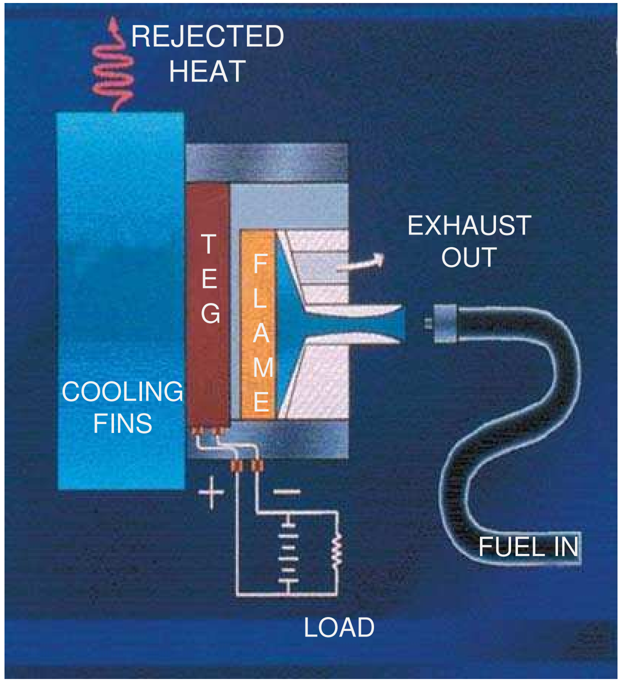
Conclusion

Radioisotope Thermoelectric Generator

- compact
- Continuous power sources
- Heat exchange on the hot side by conduction (high temperature)
- Used in deep space for several decades
- reliable
- Use nuclear fuel relatively easy to manipulate Curium-244 and Plutonium-238
- Materials used: PbSnTe, PbTe, TAGS, SiGe

TEG for remote power solutions

April 1, 2014



500 Watts 24 Volts
Natural Gas 48m^3/day
Propane 76L/day or 38kg/day

Propane 38kg/day
Heating Value 50MJ/kg → Energy per day= 1900MJ=527kW.h

500 W electric → Energy per day= 12 kW.h

Efficiency : 2.2 %

Critical application requiring highly reliable power
Low maintenance required
Long life
Extreme climatic conditions (hot, cold, wet, dry)
Remote locations

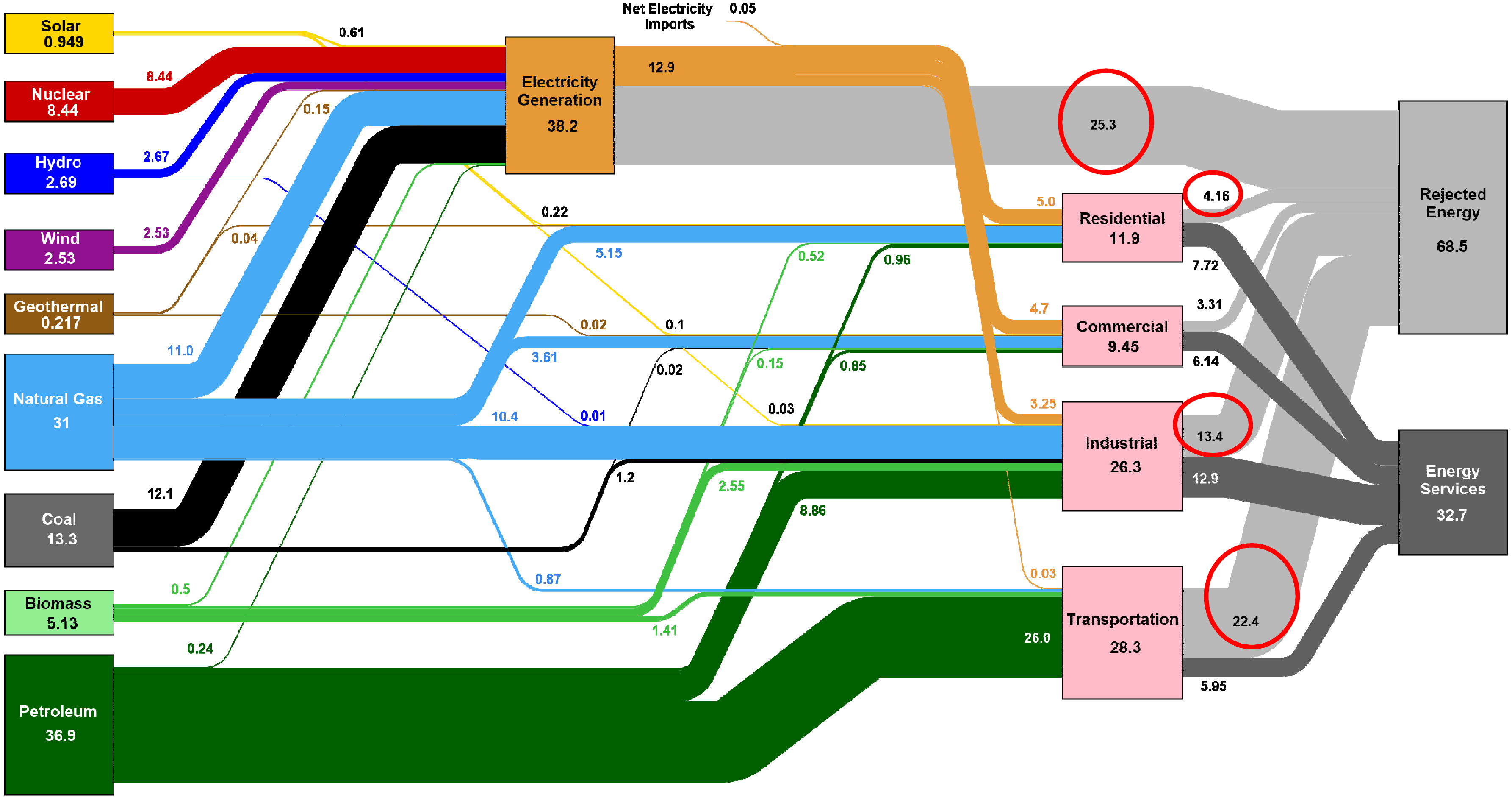
Pipeline: *550 watts*
communications system
Andes Mountains, Chile

Off shore: *200 watts*
communications and safety
equipement, multiple systems
- Thailand

Waste Heat Recovery

Estimated U.S. Energy Consumption in 2018: 101.2 Quads

Lawrence Livermore National Laboratory



Source: LLNL March, 2019. Data is based on DOE/EIA MER (2018). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL MI 410527

1 quad=2.93 10^{11}kWh=1.055x10^{18}J=293 million of MWh

Background
Roadmap for climate and energy policies

2008 European Concil

new environmental targets : "three 20 targets”
by 2020

- To reduce emissions of greenhouse gases by 20%.
- To increase energy efficiency to save 20% of EU energy consumption
- To reach 20% of renewable energy in the total energy consumption in the EU.

2014 European Concil

new environmental targets
by 2030

- To reduce emissions of greenhouse gases by 40%.
- To continue improvements in energy efficiency
- To reach 27% of renewable energy in the total energy consumption in the EU.

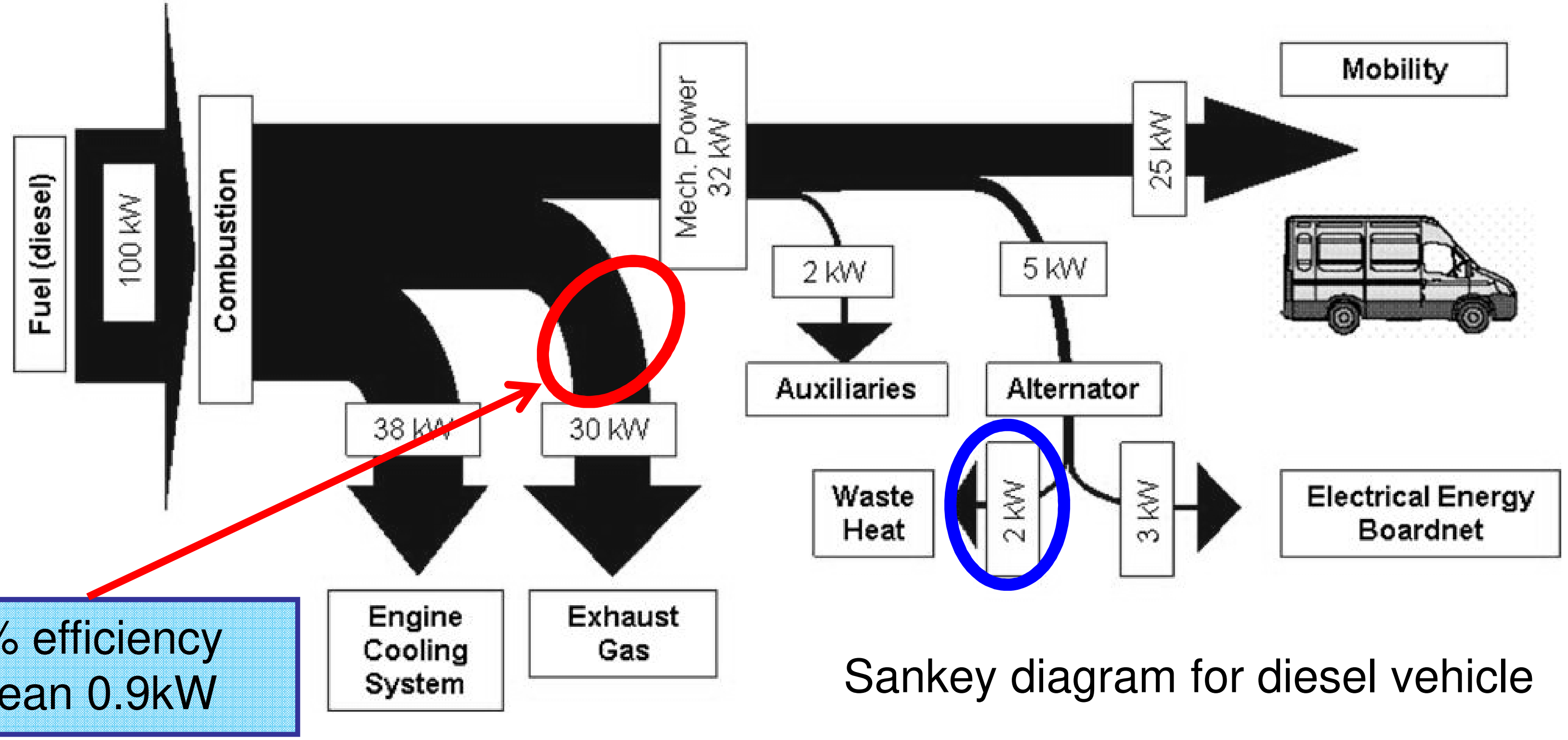
Automotive

Thermoelectric technology for automotive Waste Heat Recovery

Prototypes :

-FIAT
-FORD
-GM
-BMW
-Renoter (Renault truck Volvo …)
- Amerigon
-….

Thermoelectric technology for automotive Waste Heat Recovery



3% efficiency
mean 0.9kW

Sankey diagram for diesel vehicle

light duty trucks

Thermoelectric technology for automotive Waste Heat Recovery

New CO^2 emission performance standards

Emission target for passengers cars
130g/km for 2012
drastically reduced to 95g/km for ~~2020~~ 2021 (-37,5% for 2030 (12/2018))
fuel consumption of around 4.1 l/100 km of petrol or 3.6 l/100 km of diesel

Emission target for light duty trucks
175g/km for ~~2014~~ 2017
~~135~~ 147g/km for 2020. 5.5 l/100 km of diesel

Fine and penalties to be paid by car manufacturers that exceed EU CO^2 limits

20€ per exceeding gram starting from 2012
95€ per exceeding gram starting from 2019

ec.europa.eu/clima/policies/transport/vehicles/cars_en

Thermoelectric technology for automotive Waste Heat Recovery

Electricity produced by alternator

Conversion efficiency from fuel chemical energy to mechanical energy	➢ 25-27%
alternator efficiency from mechanical to electrical energy	➢ 60%
conversion efficiency from fuel chemical energy to electrical energy	➢ 15-16%

Electricity produced by TEG

small-medium gasoline engine at motorway driving condition is characterized by a thermal power, in its exhaust gases, of **10kW** at 600°C,

4-5% system conversion efficiency, which can be feasible with ZT=1-1.2 is enough to guarantee 400-500 Wel.

400-500W_{el} means 6-7g/km CO^2 reduction (Fiat Research Center)

Automotive Requirements for a TE Generator

Requirements

- Backpressure limit in TEG
  - Exchanger must not disturb too much exhaust gases: pressure drops very low (tens of a few millibars).
- Temperature limit for TE materials (add bypass for exhaust gases)
- Durability test requirements
- Assembly requirements
- Control and sensor requirements
- Power conditioning (DC/DC converter)
- Recycling
- Price and Performance

Possibles locations for TEG

TEG in a vehicule require

- Water supply
- By Pass
- Heat exchanger
- High Temperature and MassFlow

Integration in the exhaust system:

Advantages

- Highest recuperation potential

Disadvantages

- Exchangers : high integration effort
- Connection to cooling system
- Bypass : (flat possible but expensive)

Integration into the EGR (Exhaust Gas Recirculation) for a diesel engine:

Advantages

Easier to integrate (existing exchanger)

Control for mass flow (EGR valve)

Cooling water already there

Disadvantages

Reduced recuperation potential (5 à 35%)

Exhaust Gas Recirculation reduces NOx emissions by reducing the combustion temperature in Diesel engines.
EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders.
Gas must be cooled

A. Eder, BMW group, thermoelectrics applications San Diego 2011

HeatReCar

first light commercial vehicule equipped with a TEG

Vehicle

IVECO Daily, 2.3l Diesel engine

Design reference condition

Vehicle 130km/h
Exhaust gas temperature: 450°C
Gas flow : 70g/s (max torque), 140g/s (full load)

Target performance

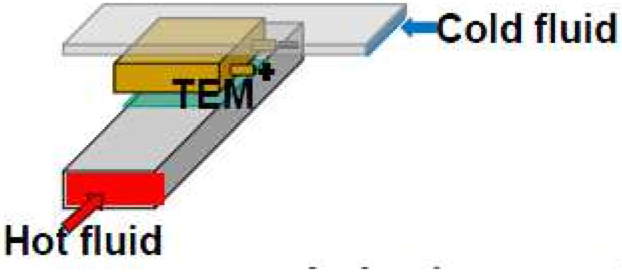
TEG electrical output 1kW

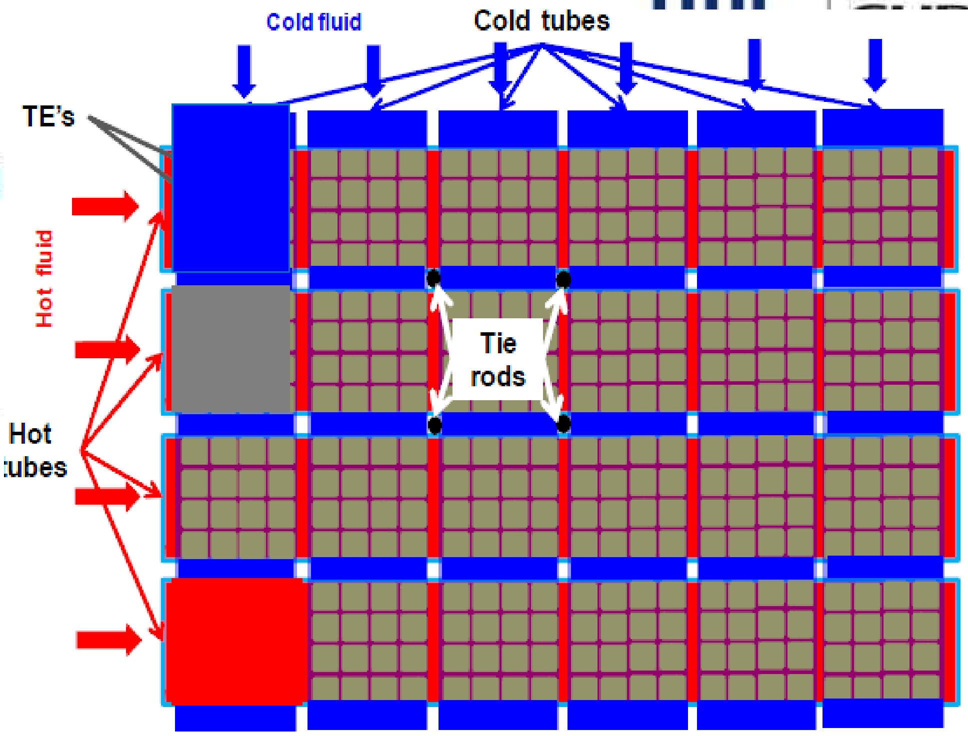
D. Magnetto 3rd International Conference Thermal Management for EV/HEV Darmstadt 24-26 June 2013

HeatReCar

first light commercial vehicule equipped with a TEG

Cross Flow architecture.

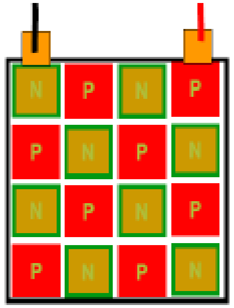




Material considered

- TAGS
- Segmented Bi2Te3-PTe
- Skutterudites: developed and manufactured at Module level
- **Bi2Te3: used for the full scale prototype manufacturing with specific Module design**

16 x 16 mm



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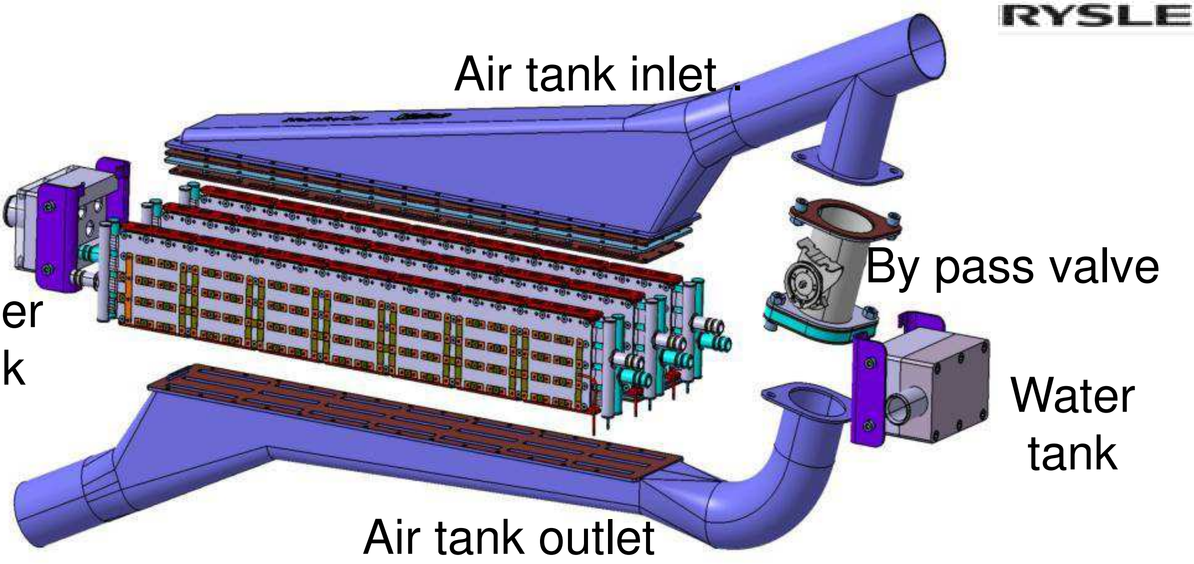
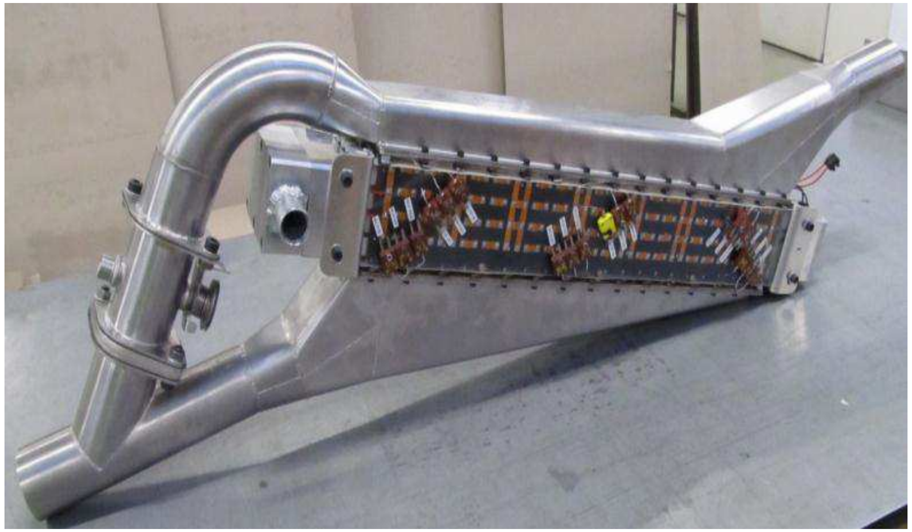
HeatReCar

first light commercial vehicule equipped with a TEG

TEG architecture.





Core size 500x100x100mm

Core weight 4kg

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HeatReCar

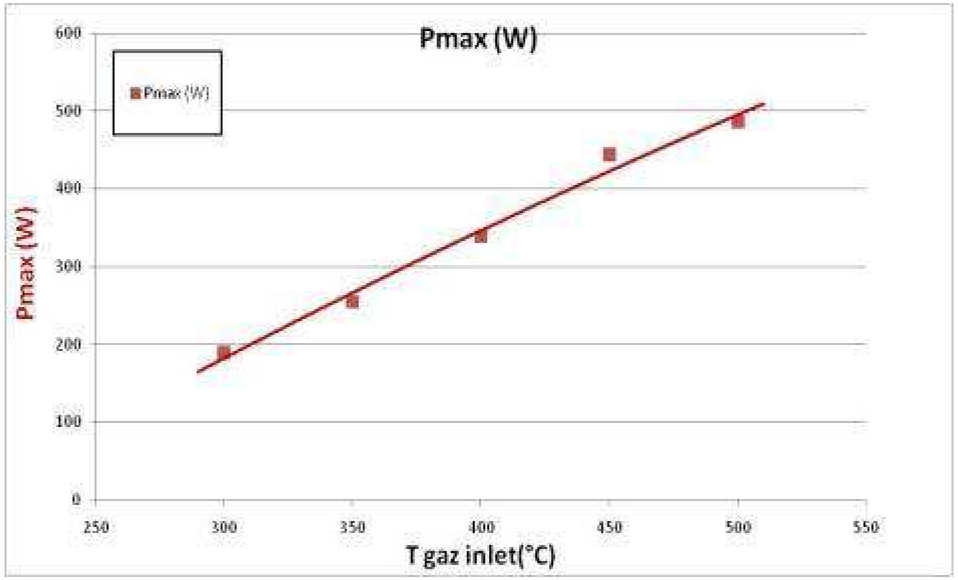
first light commercial vehicule equipped with a TEG

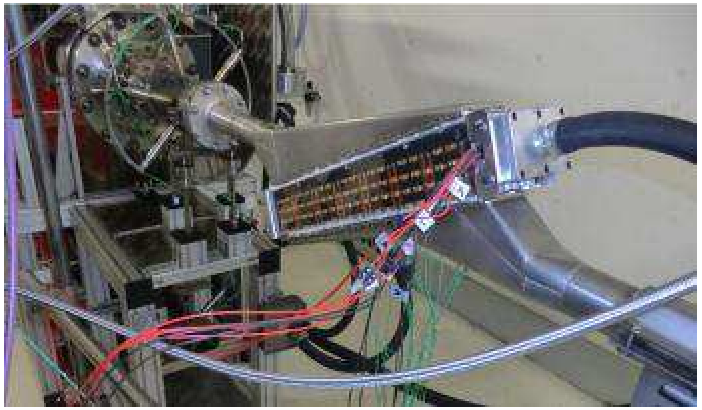
TEG performances on the test bench

Hot gaz flow: 90g/s
ΔP hot gaz: 30mbar
T hot gaz: 450°C

Cold liquid flow: 1200l/h
ΔP liquid flow: 0.15 bar
T cold flow 60°C

U: 32.1V
I : 15A
P: 482W

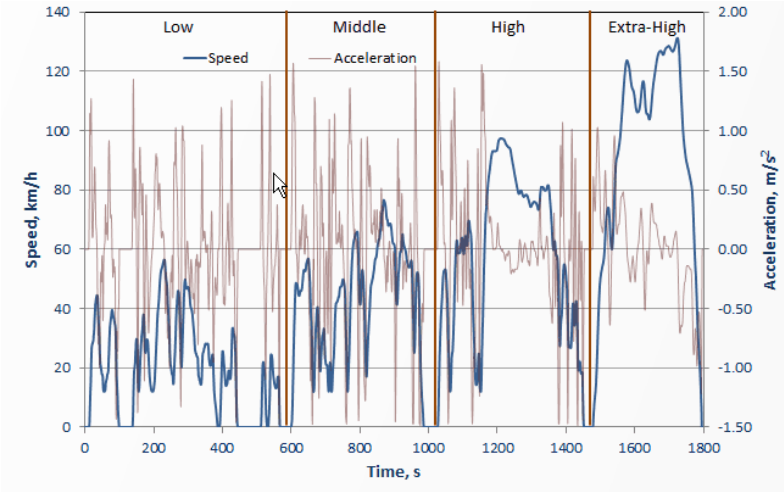




D. Magneto 3rd International Conference Thermal Management for EV/HEV Darmstadt 24-26 June 2013

HeatReCar

first light commercial vehicule equipped with a TEG



the WLTP test is expected to replace the European NEDC procedure for testing of light-duty vehicles

www.dieselnet.com/standards/cycles/wltp.php

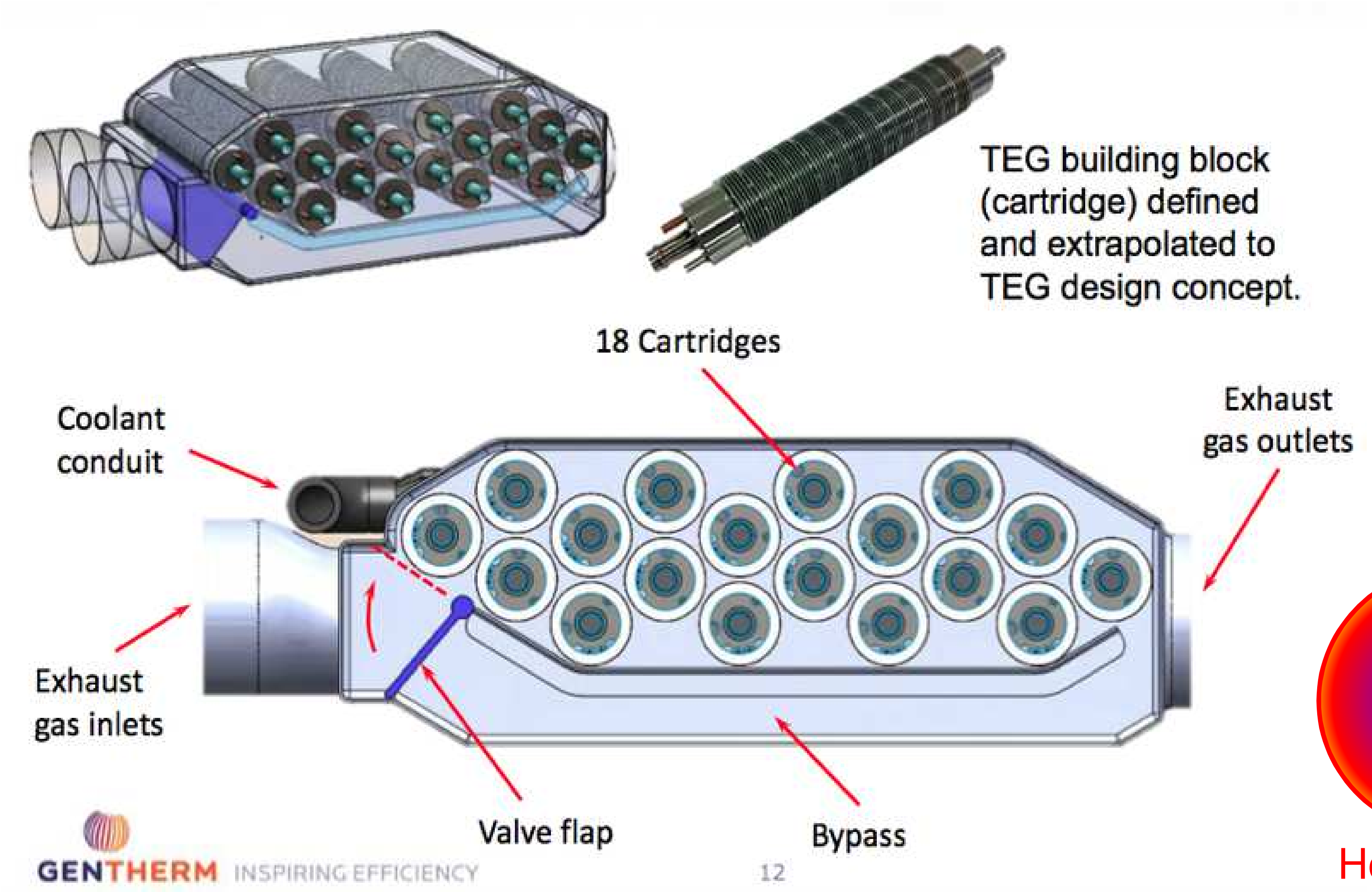
TEG on board installation

On board vehicle results summary

- 4% fuel economy improvement over the WLTC cycle has been achieved

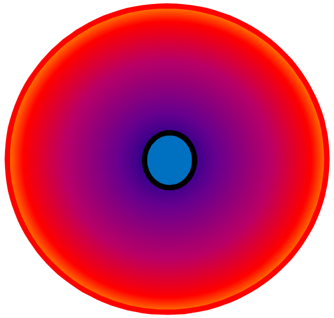
D. Magneto 3rd International Conference Thermal Management for EV/HEV Darmstadt 24-26 June 2013

GENTHERM ex AMERIGON ex BSST (BMW et Ford)



TEG building block (cartridge) defined and extrapolated to TEG design concept.

Tenneco's booth at the 2013 Frankfurt IAA Motor Show



Hot side
Larger area
Best
exchange

Automotive TEG (ATEG)

→ 2014

many projects financed on TEGs for the automotive sector
prototypes assembled and tested under real operating conditions (NDEC cycles)

2014 → ?

still publications
But no marketing of ATEG

Possible explanations :

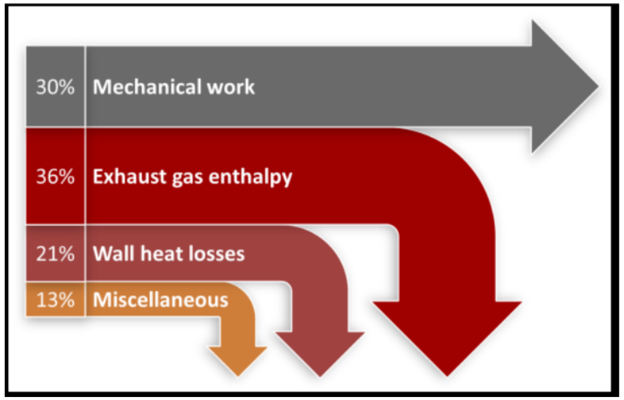
- Cost (expected 0.5 – 1 €/W)

- End of diesel and petrol cars…2030? 2040? 20xx?
  (France 2040, Britain 2040, Northway 2025, India 2030)

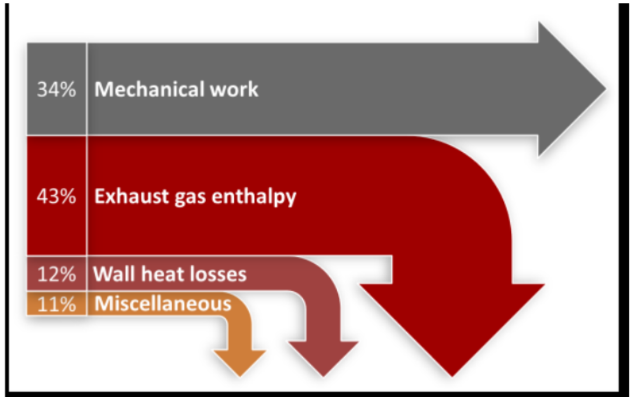
Outlook

- Decreasing cost
- **Hybrid vehicle**
- **Heavy vehicle**

hybrid vehicule



Energy flow diagram of a **conventional drive train** in average over the WLTP cycle



Energy flow diagram of a **power-split plug-in hybrid** in average over the WLTP cycle

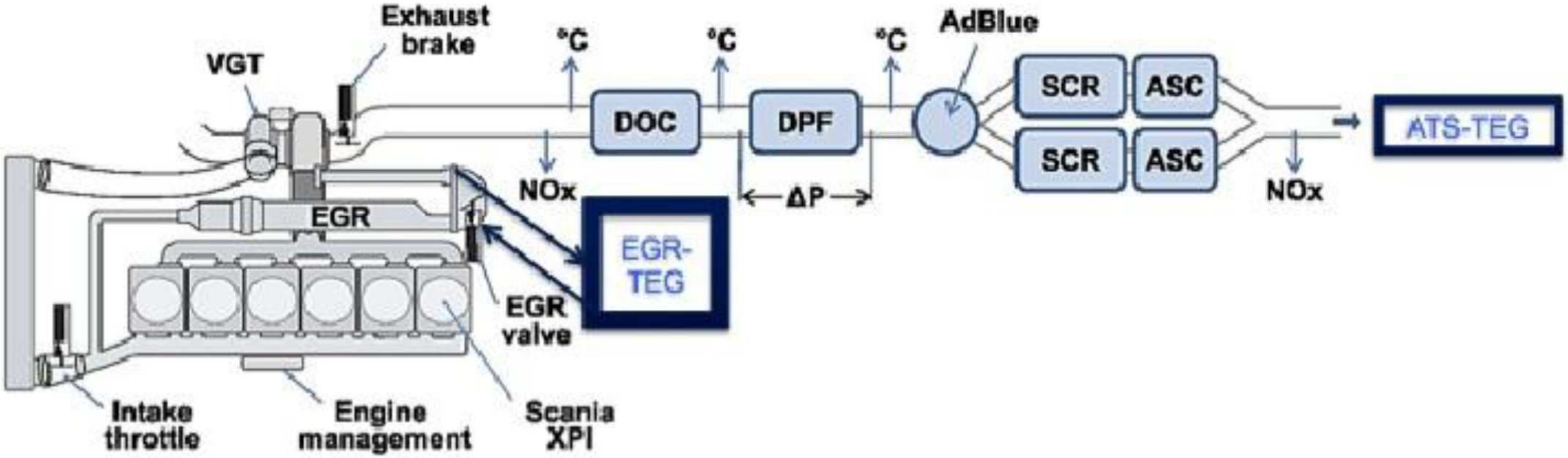
Exhaust gas temperatures and Exergetic potential for waste heat recovery in hybrid vehicles are also higher

The high potential of thermoelectric generators for WHR in hybrid vehicule Martin Kober ICT2019

Truck

Eu6 6-cylinder Scania diesel engine for Titan Truck

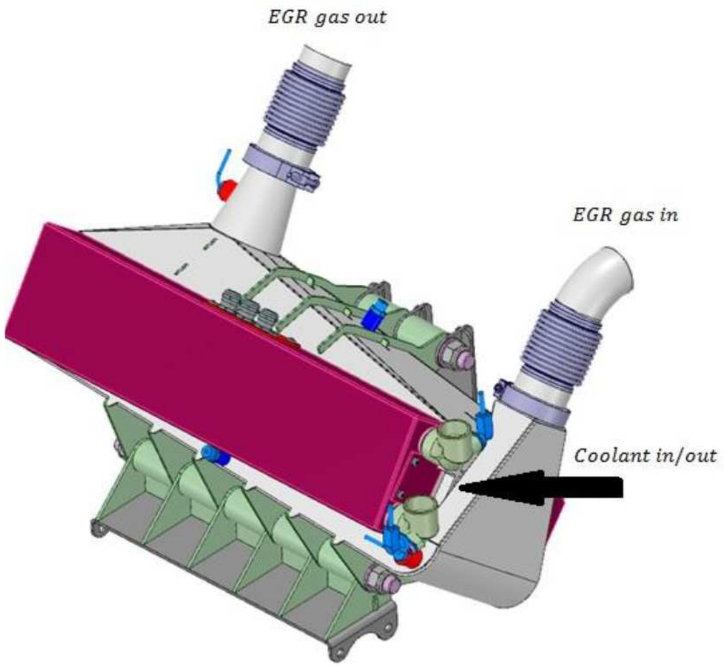
TEMs in two separate locations in the exhaust system
- behind the after treatment system, ATS (ATS need high temperature)
- in the exhaust gas recirculation, EGR system.



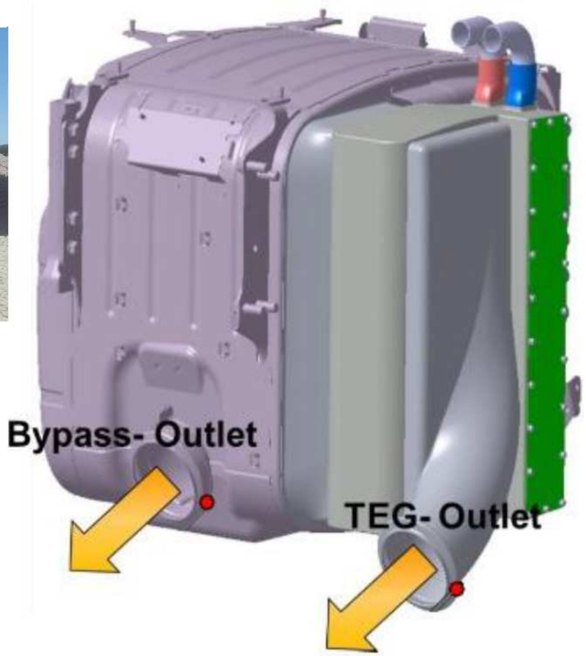
Eberspächer GmbH responsible for design and manufacture of the ATS-TEG and TitanX AB for the EGR-TEG.

2015 Waste heat recovery system with new thermoelectric materials J.Coyet F. Borgström

Truck

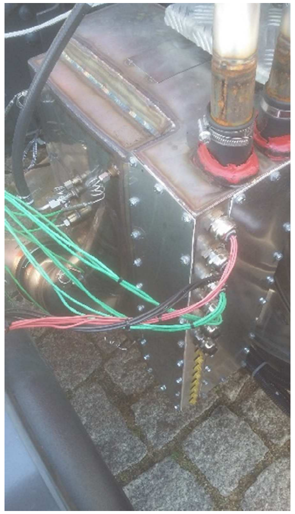


EGR-TEG



ATS-TEG

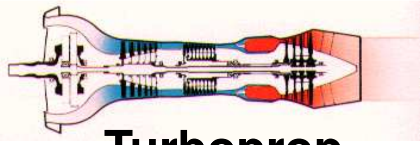
Photos ICT2015



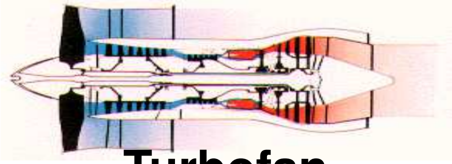
Aircraft Thermoelectric Applications

How can Thermoelectric Contribute?

Aircraft engine waste heat harvesting has large potential payoffs


Turboprop


Turboshaft


Turbofan

Advantages	**Disadvantages**
•Provides electrical power from waste heat – no fuel burn and no moving parts **• Operates over the entire aircraft flight envelope** **• Operates independent of engines and does not affect engine operations**	**•New technology and unproven** **•Cost & efficiency; further development is needed** **•Power output limited by available waste heat, space, device efficiency.**

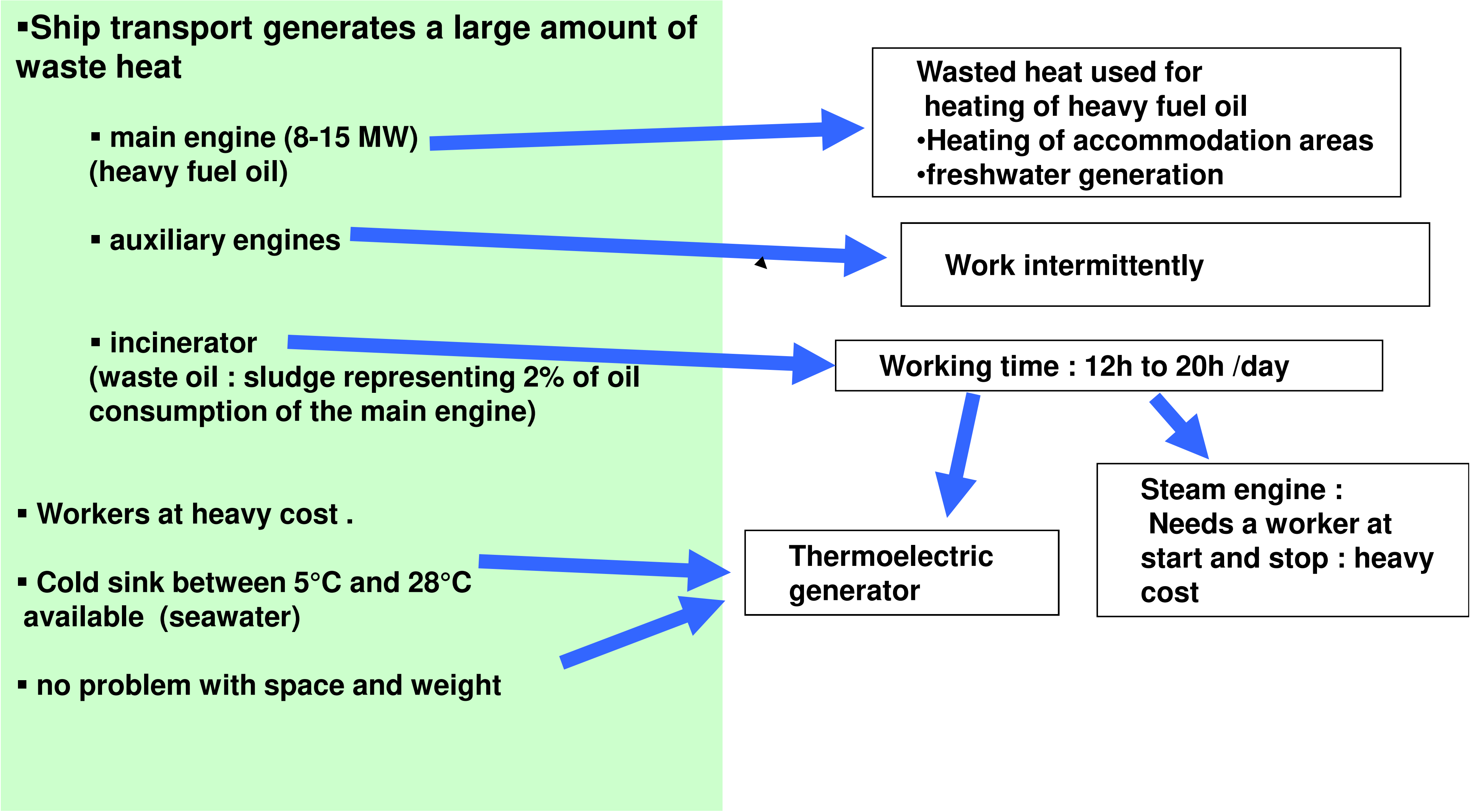
Fuel Reduction
Preliminary analysis showed that **0.5%** or more fuel reduction is achievable

Operating Cost Reduction
Average monthly fuel costs for U.S. commercial planes is $2.415B for the first 4 months of 2009 (Source: EIA)
A 0.5% fuel reduction : **$12M monthly operating cost reduction**

2009 James Huang,Boeing Research & Technology

Watt per kilo?
Permitted 0.15 kW/kg
Helicopter conical nozzle
Champier : 0.04kW/kg

Usage of Thermoelectric Generators on Ships



▪Ship transport generates a large amount of waste heat

- **main engine (8-15 MW) (heavy fuel oil)**
- **auxiliary engines**
- **incinerator (waste oil : sludge representing 2% of oil consumption of the main engine)**

▪ Workers at heavy cost .

▪ Cold sink between 5°C and 28°C available (seawater)

▪ no problem with space and weight

Wasted heat used for heating of heavy fuel oil
•Heating of accommodation areas
•freshwater generation

Work intermittently

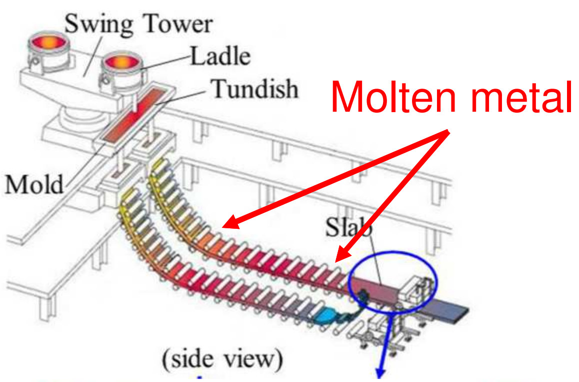
Working time : 12h to 20h /day

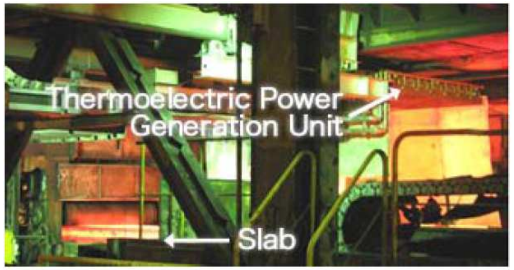
Thermoelectric generator

Steam engine : Needs a worker at start and stop : heavy cost

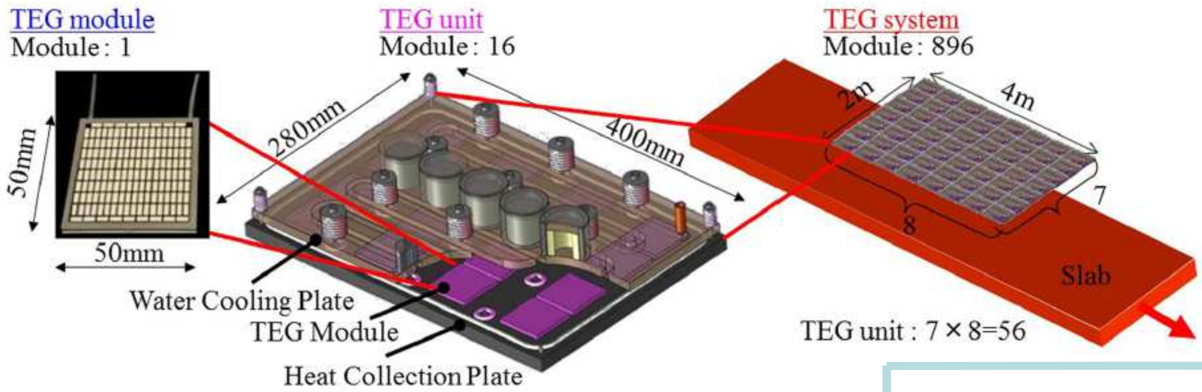
Kristiansen : incinerator 850kW, calculation : 38kW electric cost 2,7US$/W.

radiant heat in steelmaking industry



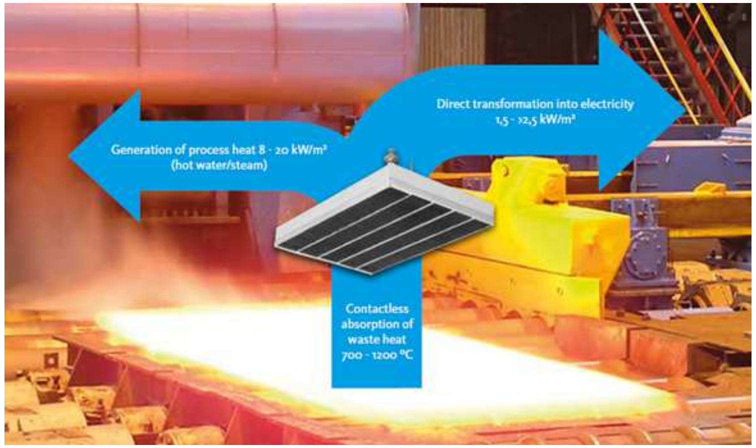


JFE Steel Corporation Japan



A TEG system (about 4 m x 2 m) using radiant heat from the continuous casting slabs
896 TE modules (56 TEG units of 16 TE modules of Bi2Te3)
The thermoelectric generation system outputs about 9 kW when the slab temperature is about 915°C

2014 kuroki Thermoelectric Generation Using Waste Heat in Steel Works



Thermagy™ heat panels:

waste heat recovery
Conclusion

New materials : light, environment friendly, cheap.

Automotive (hybrid car, trucks and farm machines)

?

Ships

Promising

Airplanes

More research is necessary

radiant heat in industry

Promising

Domestic production :
Decentralized electricity generation

Developing countries

Biomass primary energy source
(cooking, heating, domestic hot water)

Developed countries

Connection to the network is not always economically attractive

Biomass stoves
Combined Heat and Power (CHP)

Developing countries : TEG for Biomass Stoves

Biomass energy is used for basic needs : cooking and heating

Open fire

very low efficiency (5-10%)
emission of harmful black fumes
increase pressure on local forests

Rocket stove

efficiency (~35%)

T-LUD (Top Lid UpDraft)

efficiency (~40%)

improved multifunction biomass fired stove

85 % global efficiency
maxi **CO level** of 200 g/GJ

wood consumption divide by two

cooking
domestic hot water:
low temperature radiant heating
mechanical extraction no chimney

electric fan is necessary

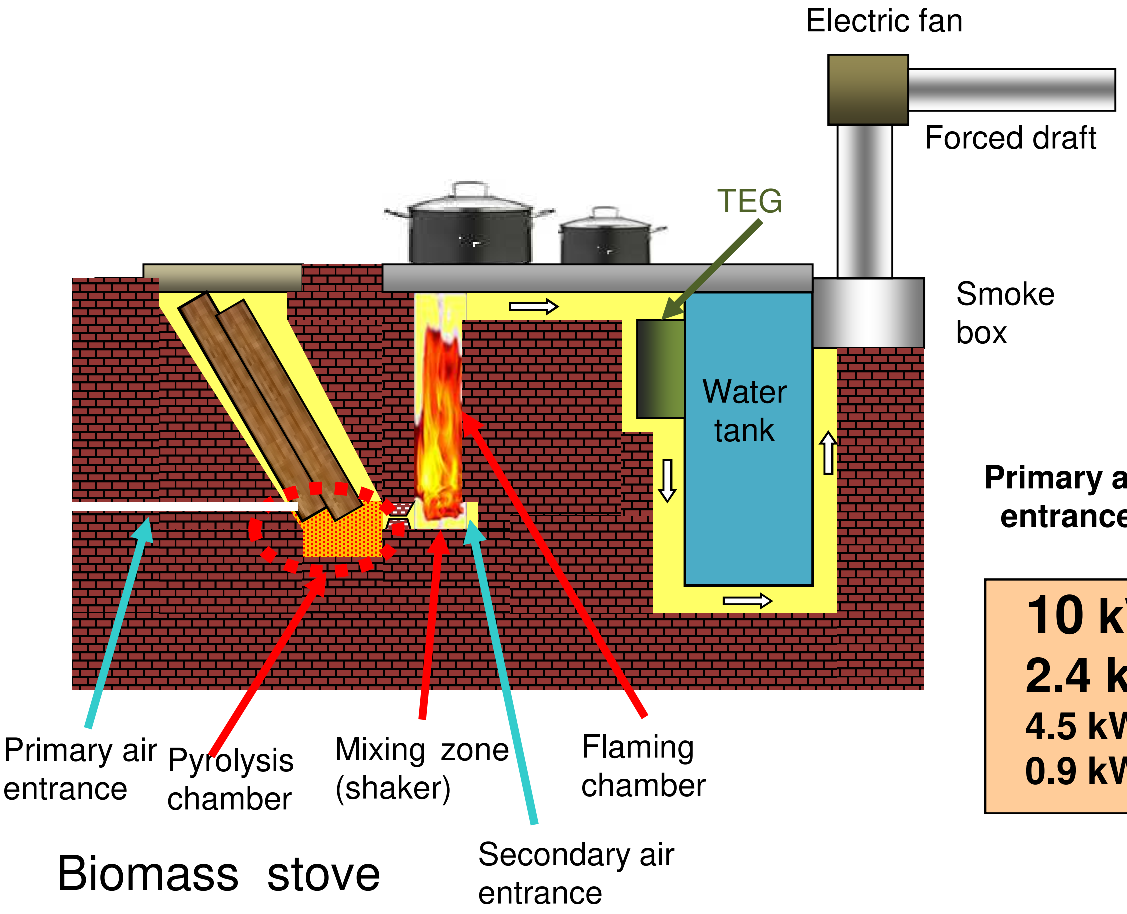
1 billion people
without electricity
in developing countries

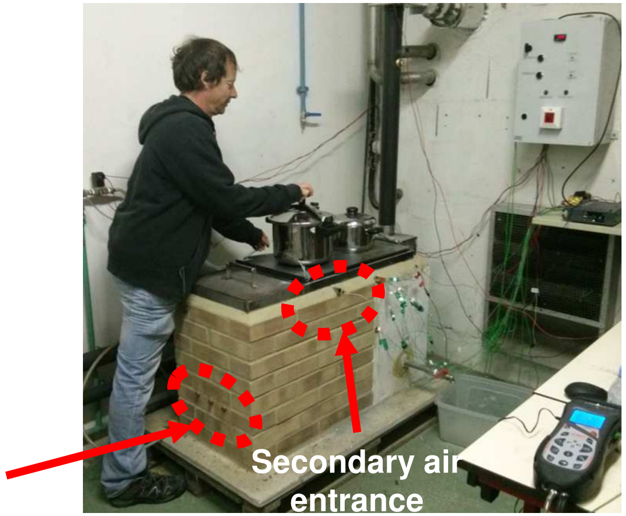
They needs electricity for light and cellular phone

Connecting to the power grid :
cost of building new landlines
from US$300 to more than US$4000
cost of distribution of electricity
from US$0.07 to US$5.1 per kWh

thermoelectric generators
are cost-effective solutions

“Planète Bois” Cooking stove and TEG





10 kW wood consumption

2.4 kW are used in heating the water

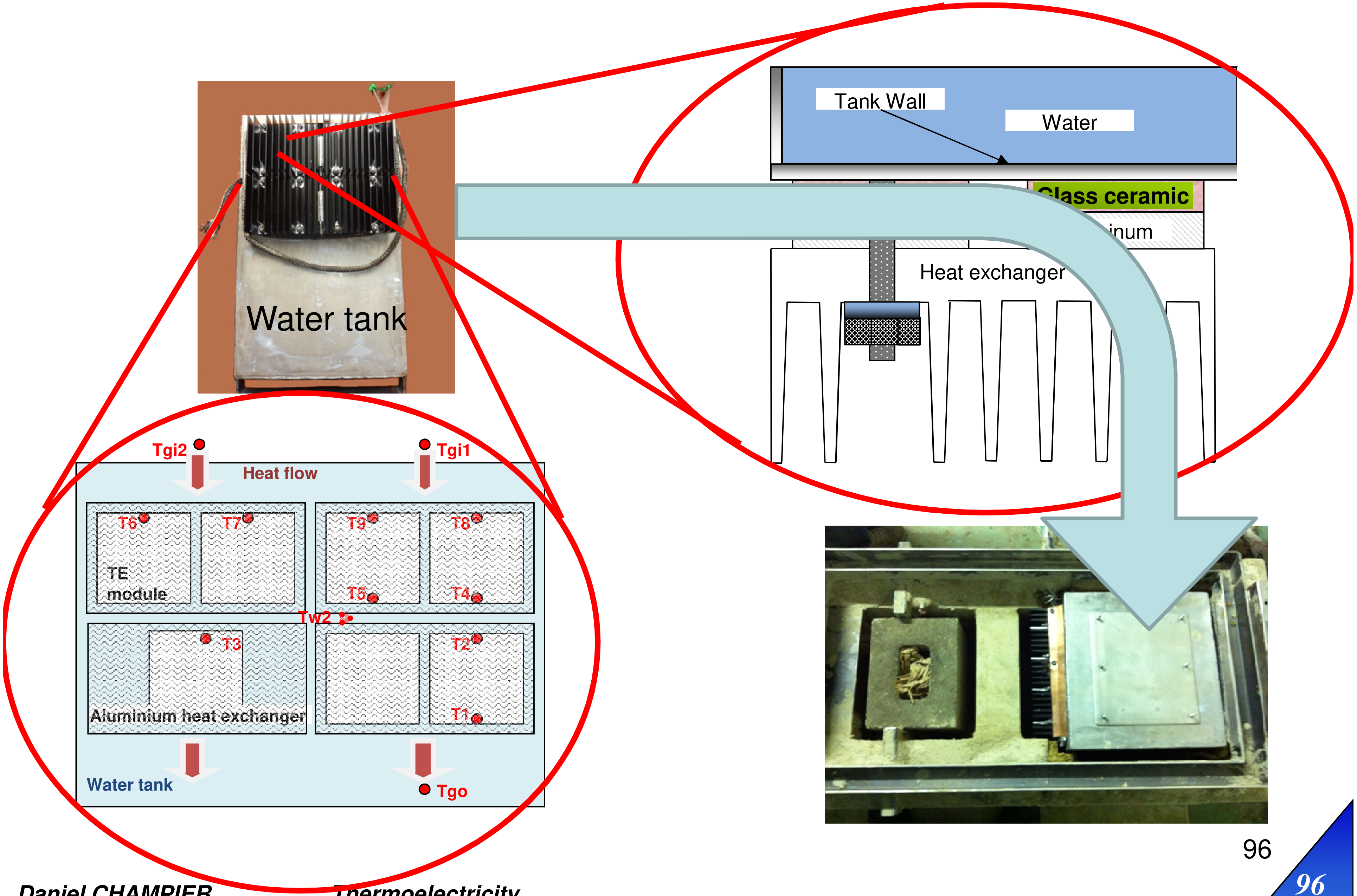
4.5 kW are used in heating the room and inertia

0.9 kW is used for cooking

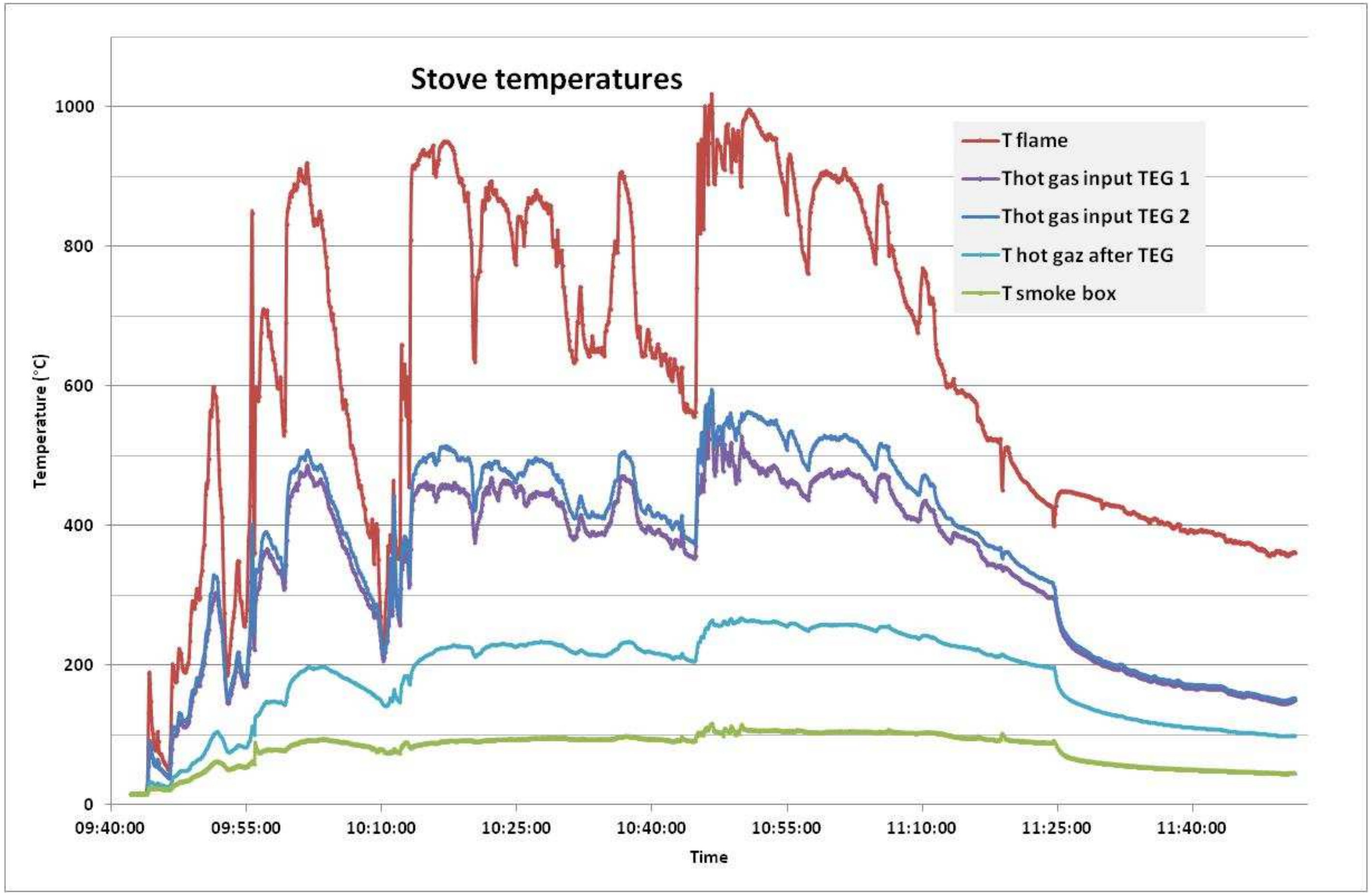
The idea is to put the TEG in a cogeneration system which simultaneously provides electric power and heat for the hot water

2015 Favarel, Champier Thermoelectricity - A promising complementarity with efficient stoves in off-grid-areas

TEG for stoves

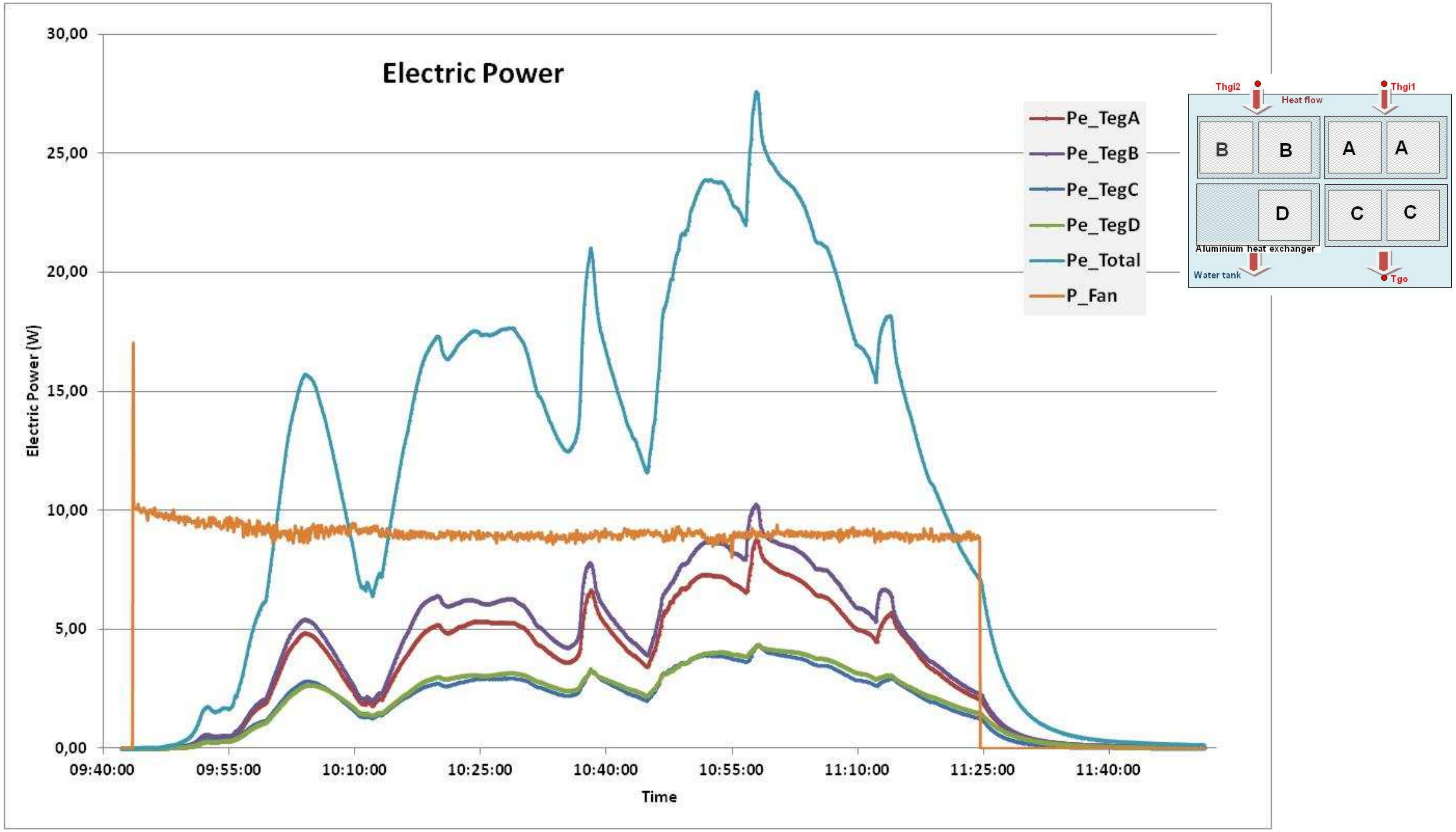


“Planète Bois” Cooking stove and TEG



Temperatures fluctuate a lot

“Planète Bois” Cooking stove and TEG



Output Electrical Energy : 23.7 W.h

Fan consumption : 15.3 W.h

TEG results.

Cycle	**one cooking** **1h30min**	**Day 1** **2 cookings**
Electrical energy produced	23.7Wh	**47,4Wh**
Average electric Power	15.8 W	
Fan consumption	15.3Wh	30,6Wh
Extra Use Use's exemple*	one phone charge 1 hours of light	**1 phone charge almost** **4 hours of light**
Major Advantage	**- Wood consumption divided by two** **- Healthy (less black fumes)** **- More comfort for women** **- low CO**	

* Phone battery of 3.7V, 1050mAh and light consummation of 4W

Cost	one sample	Big quantity
Aluminium	60€	30€
electronic part	31€	15€
TE modules	75€ **x6**	27€ **x 6**
TE generator	541€	207€

TE generators are cost-effective solutions for off-grid households with low income.

SIAME prototype
Advantages of TEG's

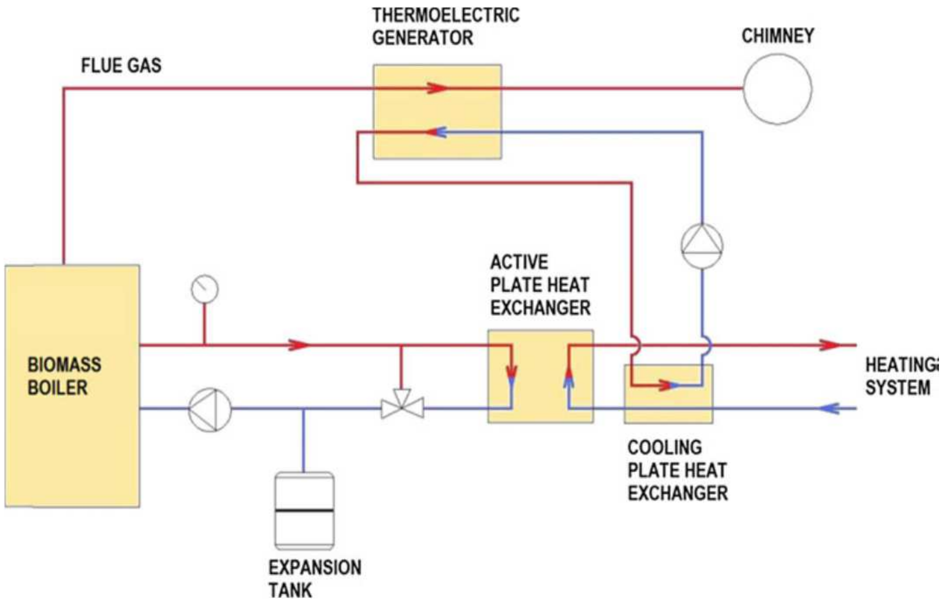
The advantages of thermoelectric generator are :

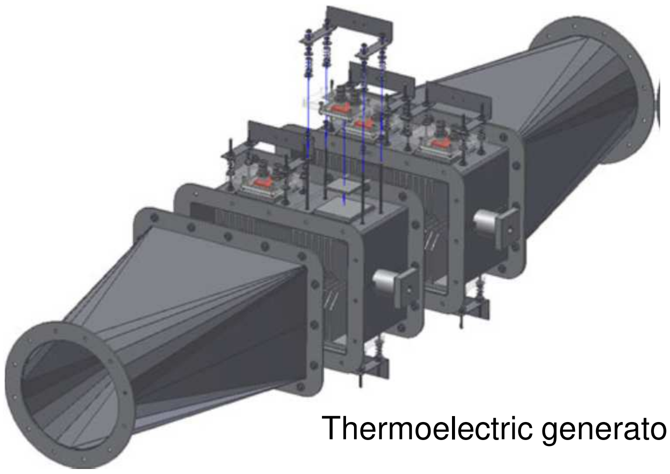
- It does not need extra energy from the stove.
  - It will use the heat flux between the gas and the water tank
  - It will only convert a small part into electrical energy.
- It is incorporated into the cook stove:
  - it requires no electrical link with the outside world, unlike solar panels, or manipulation of battery.
- The maintenance is very light:
  - nothing is moving,
  - everything is inside the house,
  - only the battery needs to be changed at the end of its life.

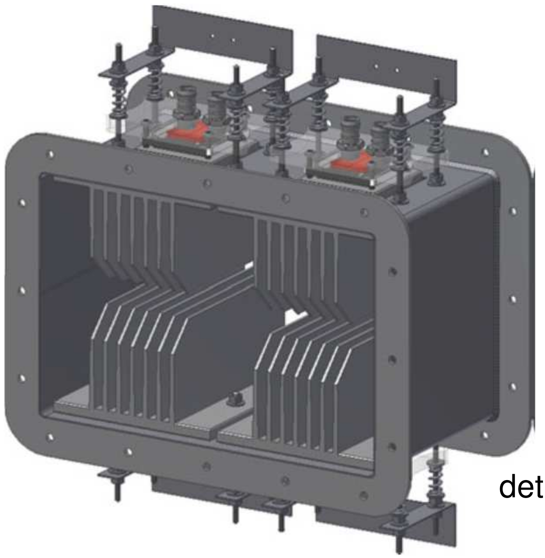
- The generator produces when the stove is on, day and night in good or in rainy weather (monsoon period) unlike solar panel.

- The battery does need to be oversized as each use of the stove recharges the battery unlike solar system where you need to store energy for the cloudy days.

TEG in a biomass boiler




Thermoelectric generator.


details

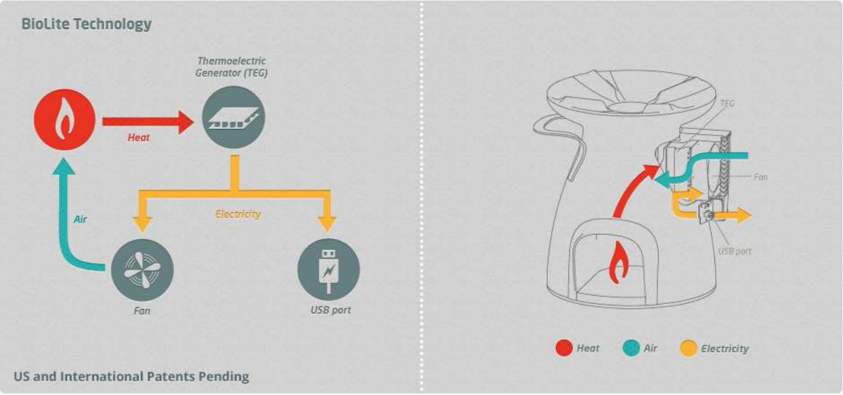
automatic biomass boiler Verner A251.1 with nominal rated heat output of 25 kW

$\Delta T = 113K$.
Maximum measured output power 8.5 W.
Temperature lost by the flue gas in the TEG : 40K

power for self-sufficient operation of the combustion and heating system without any negative influence on the boiler operation.

2013 Brazdil Thermoelectric power generation utilizing the waste heat from a biomass boiler Journal of ELECTRONIC MATERIALS,

Biolite
HomeStove and CampStove

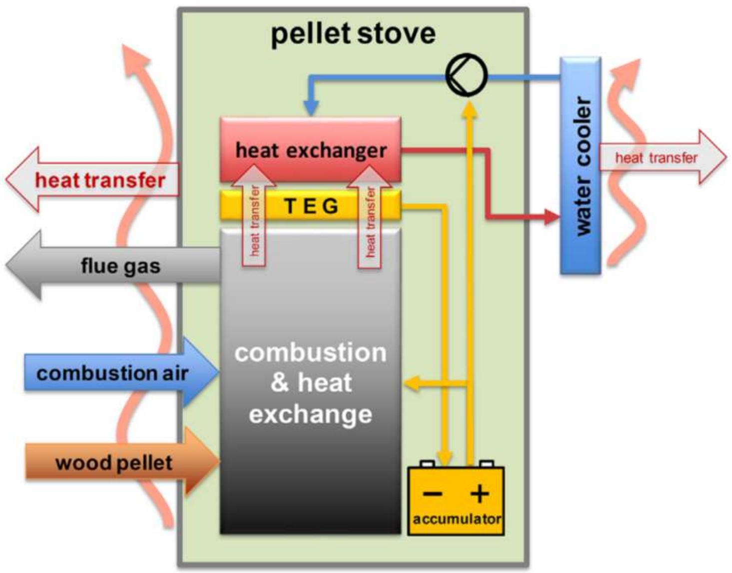


https://biolite.boutiquesinternet.fr
99,95€ livraison gratuite

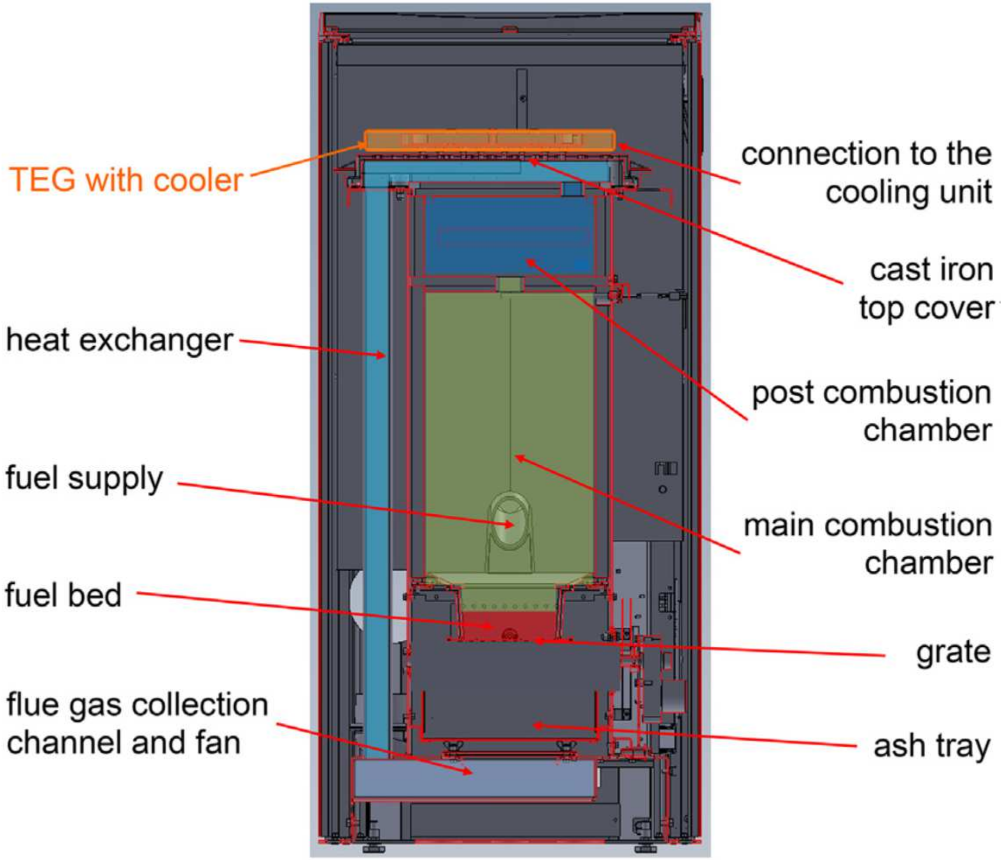
USB 3W 5V

micro CHP would pellet stove

BIOS BIOENERGIESYSTEME Graz
RIKA Micheldorf, Austria



12 TEMs



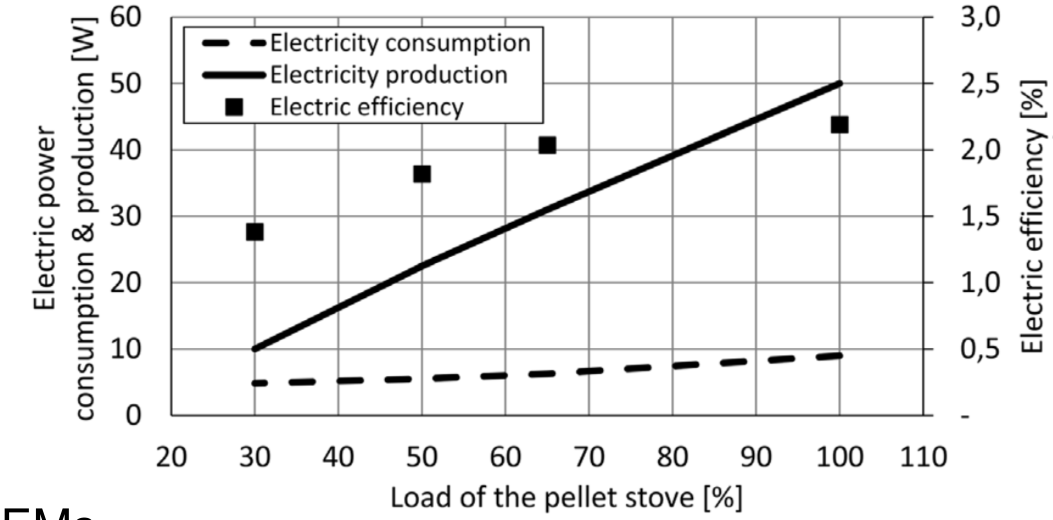
Cross section of the pellet stove CHP technology.

2018 Obernberger Development of a new micro CHP pellet stove technology, Biomass and Bioenergy

micro CHP would pellet stove thermal capacity 10.5 kW

BIOS BIOENERGIESYSTEME Graz
RIKA Micheldorf, Austria

Testing plant



12 TEMs

surplus electricity production of about 40W at nominal load

at 30% part load the electricity demand of stove covered by the TEG.

Can operate **off-grid**

2017 :Its market introduction is planned by RIKA within 2018

?

Stove “Seebeck 250W”

Seebeck 250W

Made in Germany by Thermoelect GmbH

wood gasification and two combustion chambers

upper chamber is filled with logs

Exhaust gases are redirected to a second lower chamber by combustion nozzles for afterburning.
hot exhaust gases from the lower chamber tunnel flow into the flues of the back of the furnace
Lead to the chimney pipe around a water heat exchanger.
On the way up, the exhaust gases heat up the water in the heat exchanger.

Seebeck 250W : generation of heat, domestic hot water and electricity with thermoelectric generators (TEGs) with 250 watts

- 10-20 kW for heating and service water with high efficient wood-nano-cogeneration unit
- 60 liter filling volume for wood (logs) with a size of 33-40 cm
- up to 4 hours burning per wood charge
- a boiler for the heating room

250 watt of electricity for the entire house :
- Furnace as energy consumer (control system + fans) 50 W
- Boiler pump 20 W
- Heating circuit pump 15 W
- LED lighting, 14 LED lamps each 5 Watt 70 W
- Fridge/Freezer A++
  (Privileg PRB376, 196 l Fridge, 111 l Freezer, peak load 150 W)
233kW/h each year with average load of 27 W)
- MacBook Pro in grid operation (100% brightness, MP4 Film) 20 W
- Charge iPhone 10 W
- Charge tablet 10 W

www.he-energy.com/en/seebeck_eng.html

2019 stoves on the market

Ecofan : heat-powered fans for stove heaters

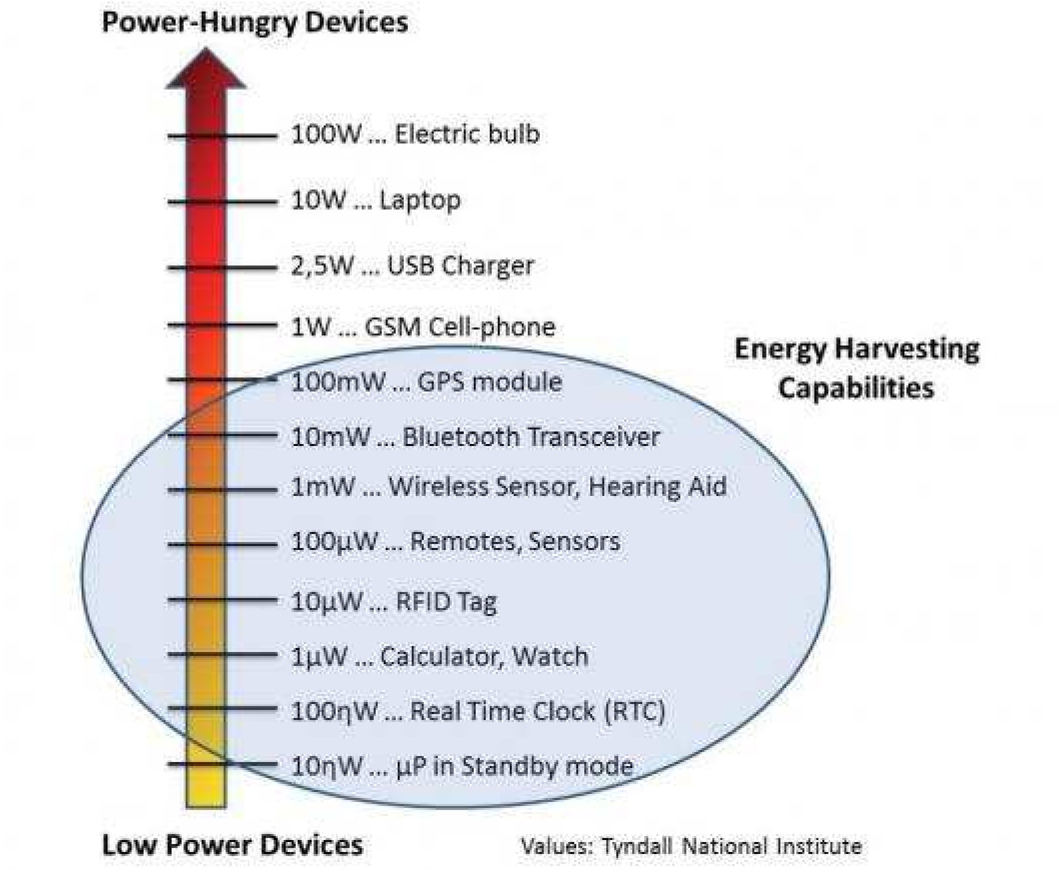
The airflow created by the fan distributes the warm air from the stove more evenly in the room.
Average fuel saving of 14% for a range of standard test conditions Maintain user comfort levels over extended periods.

$99.99

Time taken to reach 20°C from a cold start of 17°C in a standard test environment.
With fan: 68 minutes vs. **No fan**: 110 minutes

www.caframolifestylesolutions.com

Energy Harvesting for Low Power Electronics



Power-Hungry Devices

100W … Electric bulb
10W … Laptop
2,5W … USB Charger
1W … GSM Cell-phone
100mW … GPS module
10mW … Bluetooth Transceiver
1mW … Wireless Sensor, Hearing Aid
100µW … Remotes, Sensors
10µW … RFID Tag
1µW … Calculator, Watch
100ηW … Real Time Clock (RTC)
10ηW … µP in Standby mode

Energy Harvesting Capabilities

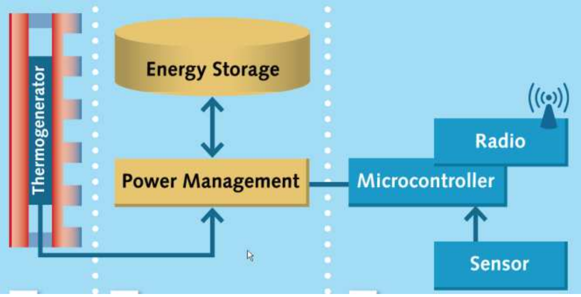
Low Power Devices

Values: Tyndall National Institute

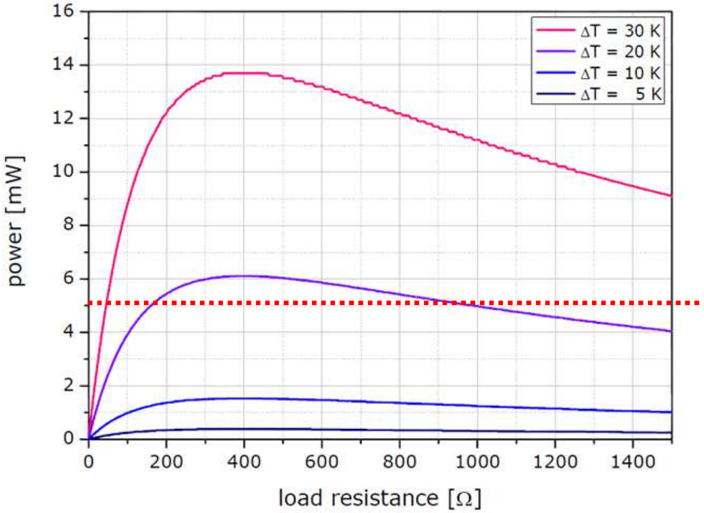
Energy Harvesting for Low Power Electronics

Modern wireless sensor modules require only ~100 µW -10mW
Internet of Things (IoT)

Take a small portion of a lost flow of 'primary' energy, and convert it into a small flow of USEFUL electrical energy.



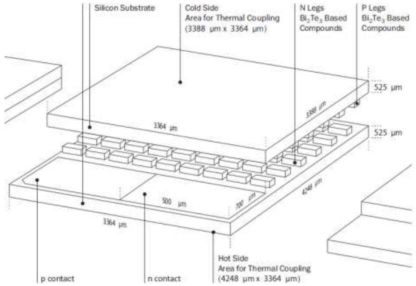
Every technical process produces waste heat



5mW is enough for most microsensor

Micropelt thermogenerator offers a high density of up to 100 thermoelectric leg pairs per mm2

MPG-D751 dimensions (schematic drawing)



Electrical:

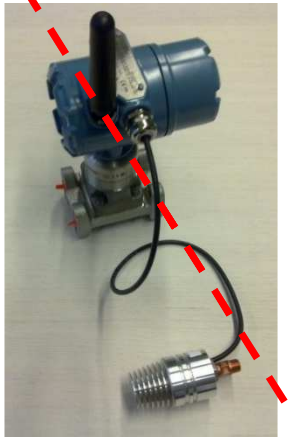
- Thermo-Voltage: $u_{TEG} = 0.14$ V/K
- Electrical Resistance: $R_{TEG} \sim 350\Omega$
- Thermal Resistance: $R_{th} = 12{,}5$ K/W

4.2mmx3.3mmx1mm

http://www.micropelt.com

Energy Harvesting for Low Power Electronics

~~**Emerson WiHART**~~
~~**Differential Pressure Transmitter**~~



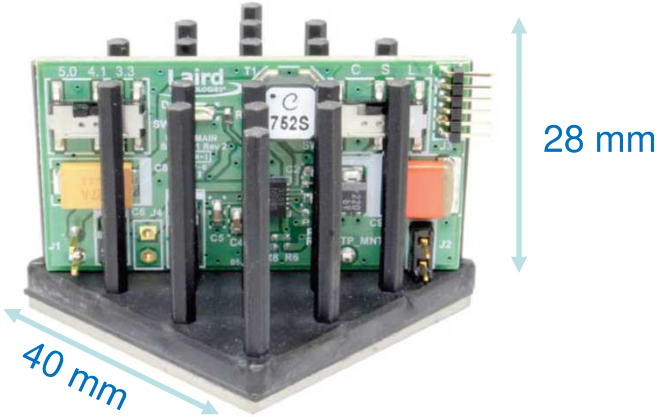
~~**Use heat from 15 mm pipe**~~

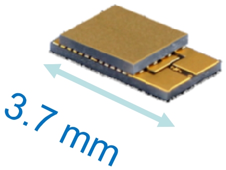
~~**Output power 3.5mw**~~
~~**at 60°C and ambiant 25°C**~~

~~**Applications :**~~
~~**Wireless sensors**~~
~~**Data loggers**~~
~~**Direct valve control**~~
~~**Wireless pneumatic control**~~

~~http://www.micropelt.com~~

WPG-1 mounted vertically on side of oven



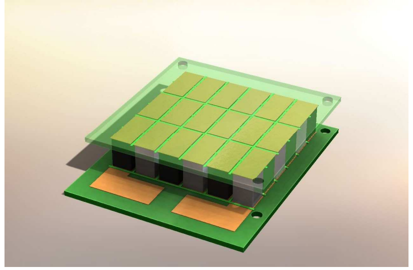


eTEC HV3

Laird technology

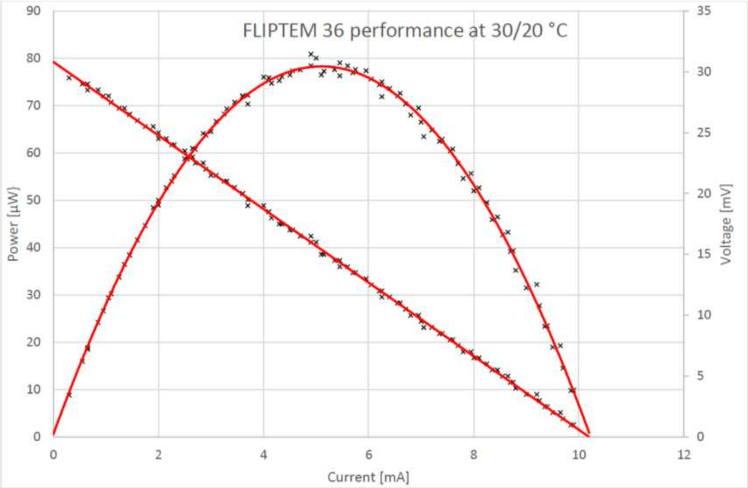
Energy Harvesting for Low Power Electronics

Fliptem 36



Zn_4Sb_3 & Mg_2SiSn

www.tegnology.dk



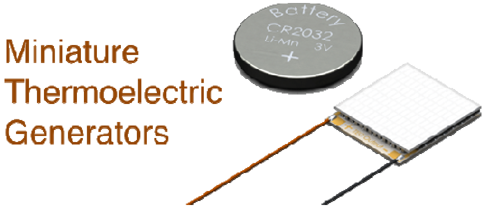
Electrical temperature monitoring
Small in size - ø30mm x 50mm
Hygienic and waterproof
Environmentally friendly
No hazardous materials
Sustainable - no batteries
Long lifetime - { 20 years }

Sensever

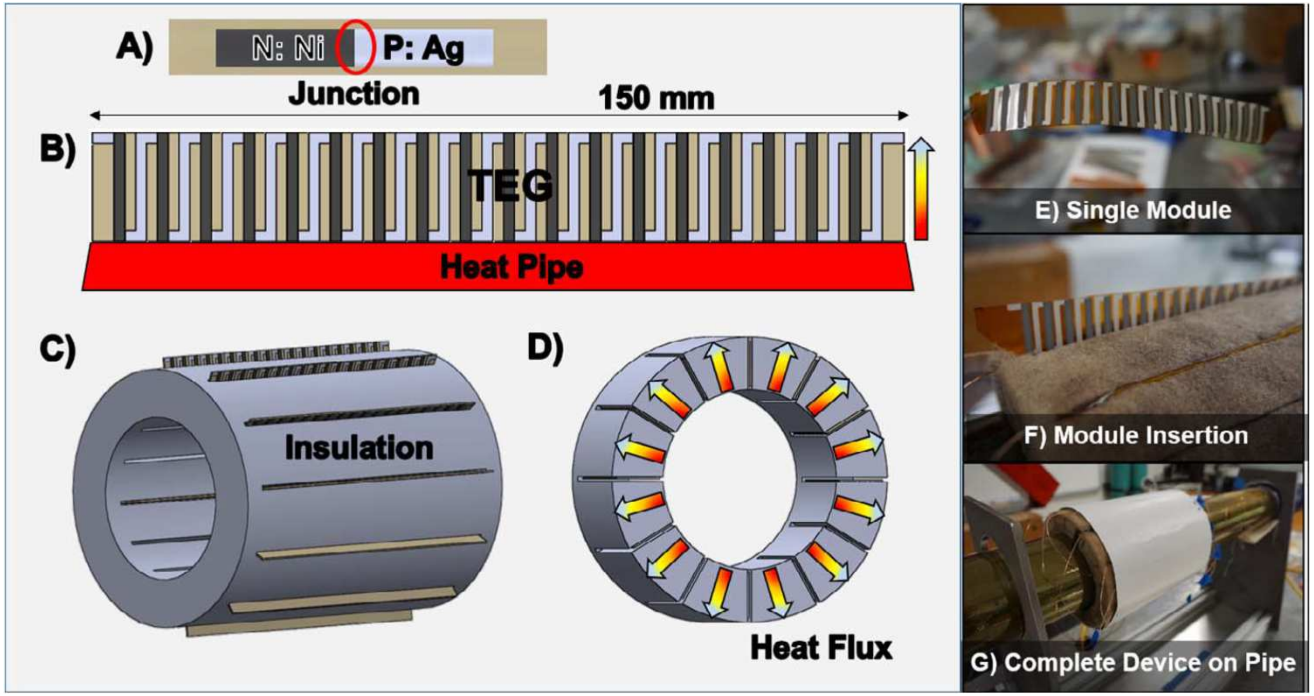
Self powered hot pipe alert.

easily installed on any pipe which could cause injury due to its extreme heat. A light and/or optional wireless signal is emitted when the pipe temperature exceeds the programmable preset threshold, alerting that the pipe is hot.

Starting from 2013 TEC Microsystems GmbH
N-Type composition: BiTeSeS
P-Type composition: BiSbTe
www.tec-microsystems.com



Printed metallic thermoelectric generators for powering wireless sensors



flexible TEGs fabricated from low cost, screen printed (Siebdruck) silver and nickel inks

A)One junction composed of n-type nickel (Ni) and p-type silver (Ag)) inks,
(B) Printed thermoelectronic module consisting of 35 Ag/Ni couples

- Ag element 2 mm width
- Ni element 3.5 mm width,

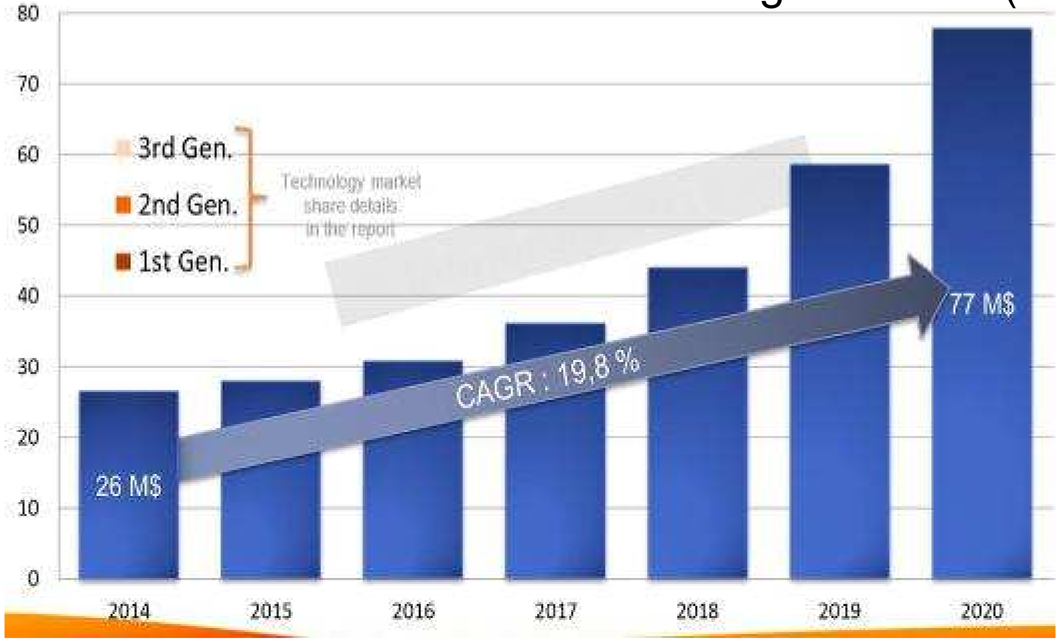
(C) Insertion of 12 modules into steam pipe insulation to create 420 junction device,
(D) Cross section view of radial heat transfer through insulation,
(E–G) Images of a flexible 35 junction module inserted into the insulation with a cover in place.

2017 Iezzi Printed metallic thermoelectric generators integrated with pipe insulation for powering wireless sensors Applied Energy

Conclusion

- Micropelt stopped production of TEM
- Laird : no mass production, 11 pieces available on digikey
- New actors :
  - TEGNOLOGY
  - TEC Microsystems
  - ….

Annual market for sub-watt thermoelectric generators (TEGs)



market research firm Infinergia LLC (Grenoble, France).

Solar Thermal to Thermoelectricity

Heat flux through a thermoelectric leg

$\Delta T \approx 100K$

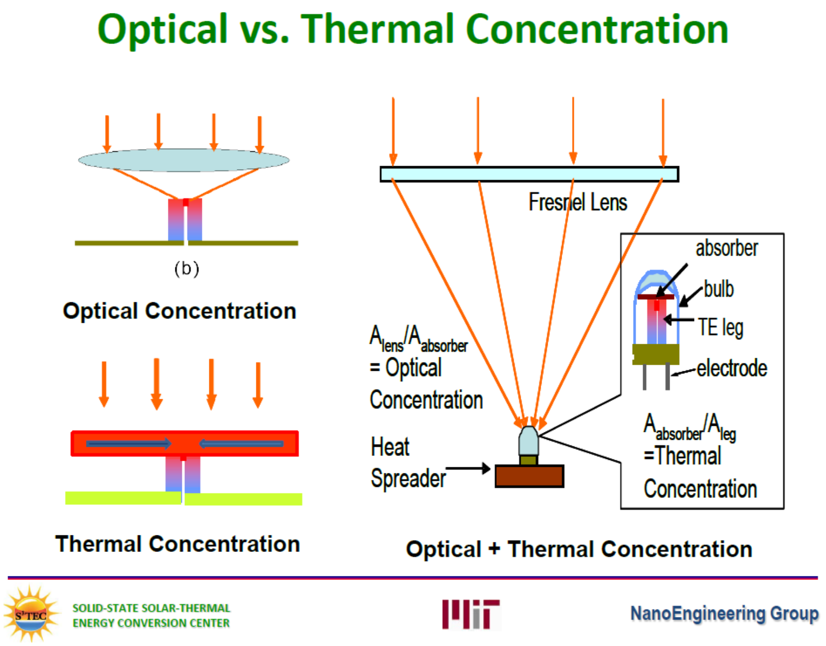
$$\frac{q}{A} \approx \lambda \frac{\Delta T}{L} \approx 1 \cdot \frac{100}{0.001} = 10^5 \, W/m^2$$

$\lambda \approx 1 \; W.m^{-1}K^{-1}$

$L \approx 0.001m$

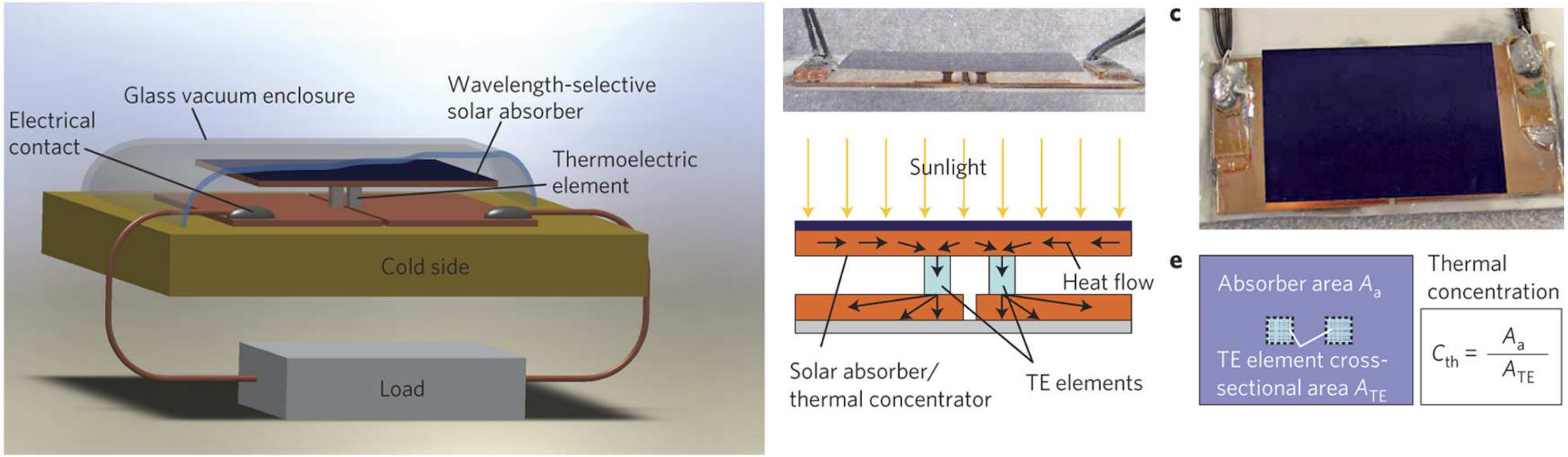
Solar insulation: ~ 1 000 W/m²

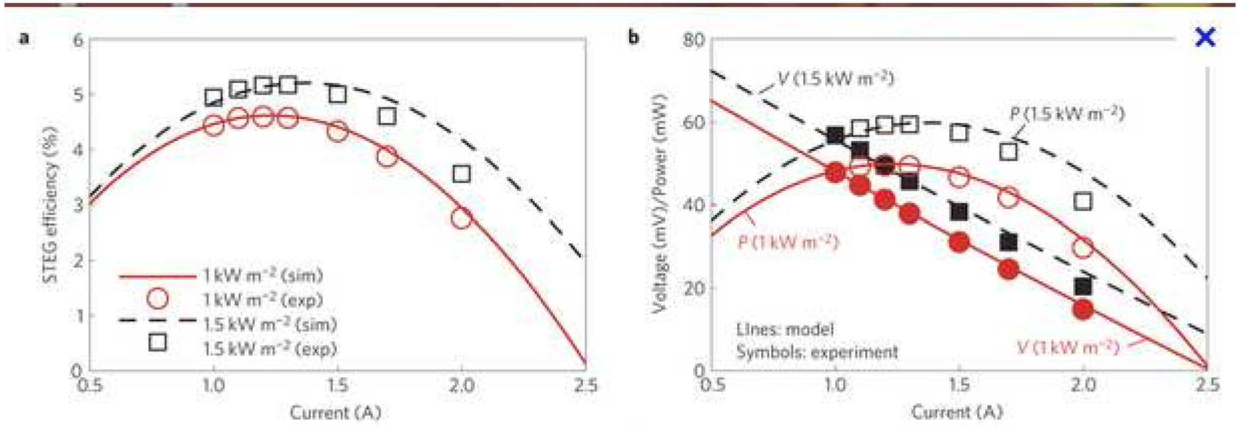
Need to concentrate heat by ~100 times



Optical vs. Thermal Concentration

Solar Thermoelectrics STEG





The developed solar thermoelectric generators (STEGs) achieved a peak efficiency of 4.6% under AM1.5G (1 kW m^{-2}) conditions.

Kraemer High-performance flat-panel solar thermoelectric generators with high thermal concentration Nat mat 2011

Conclusions

Today

niche markets with high added value

- space and extreme environments where liability is critical
- Self powered sensors (IoT)
- CHP stoves

Soon

Industrials markets

- Transports (automotive ? and ships)
- Combined heat and power system
- Developing countries
- steel industries
- Self powered sensors (IoT)

Future

- Transports (planes)
- Solar ?
- Humans uses (organics TEG)

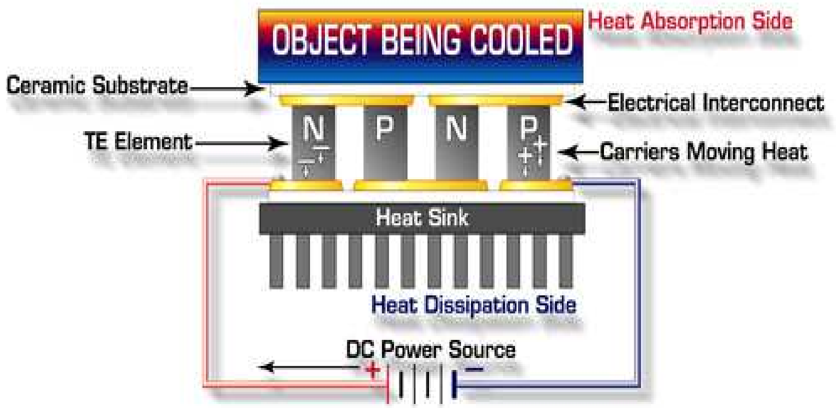
New materials

Cheap
Light weight
Environment friendly
Temperature range

research outlook

- Materials
- Design
- Optimization
- New applications

thermoelectric cooling and heating



By applying a low voltage DC power to a TE module, heat will be moved through the module from one side to the other.

a change in the polarity of the applied DC voltage will cause heat to be moved in the opposite direction.

Consequently, a thermoelectric module may be used for both heating and cooling thereby making it highly suitable for precise **temperature control applications**

Coefficient of performance

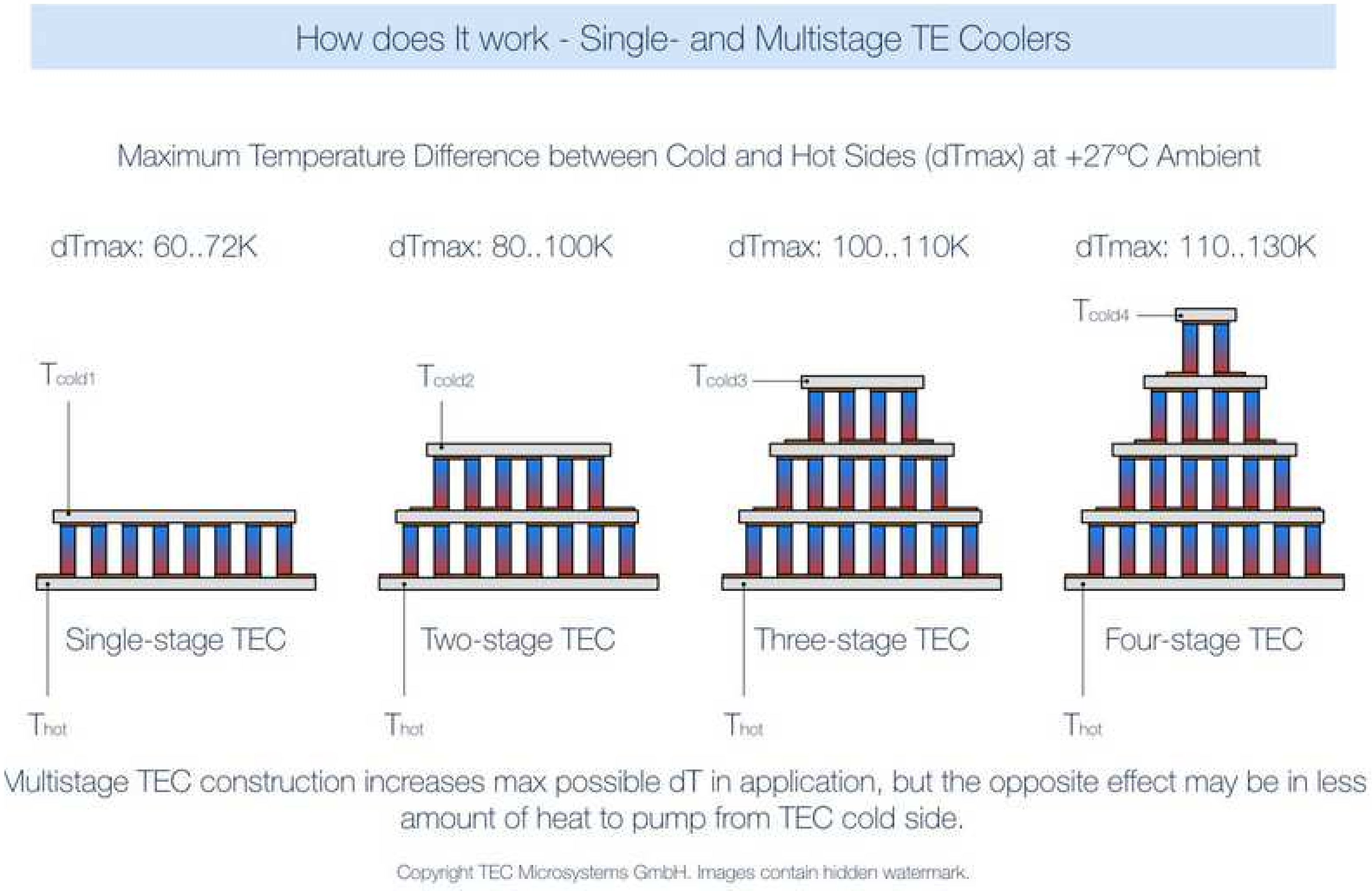
$$COP_{\max} = \frac{Qc}{We} = \frac{Tc}{\Delta T}\,\frac{\sqrt{1+zT} - \frac{Tc}{Th}}{\sqrt{1+zT} + 1}$$

Maximum temperature difference

$$Th - Tc = \frac{1}{2} ZTc^2 \approx \frac{Tc}{2} ZT$$

Tc in Kelvin

Thermoelectric optoelectronics applications



How does It work - Single- and Multistage TE Coolers

Maximum Temperature Difference between Cold and Hot Sides (dTmax) at +27°C Ambient

Multistage TEC construction increases max possible dT in application, but the opposite effect may be in less amount of heat to pump from TEC cold side.

http://www.tec-microsystems.com

thermoelectric cooling and heating

advantages

Thermoelectric modules offer many advantages including:

- No moving parts
- Small and lightweight
- Maintenance-free
- Acoustically silent and electrically “quiet”
- Heating and cooling with the same module (including temperature cycling)
- Wide operating temperature range
- Highly precise temperature control (to within 0.1°C)
- Operation in any orientation, zero gravity and high G- levels
- Cooling to very low temperatures (-80°C)

drawbacks

- fall of COP when the temperature difference increases
- high dependence to room temperature

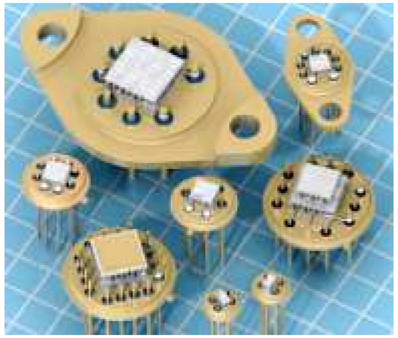
Cool only where you need ≠ conventional systems

two mainstream directions :

- electronics and photonics, particularly optoelectronics and laser techniques
- low power cooling (<500W)

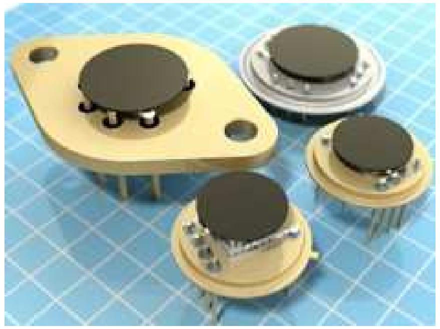
Thermoelectric optoelectronics applications

commercially during recent decades



Miniature Thermoelectric Coolers for Telecom Applications

Laser Diodes and Superluminescent Diodes
X-Ray and IR- Sensors
Photodetectors and Photomultipliers
Avalanche Photodiodes (APD)
Focal Plane Arrays (FPA)
Charge Couple Devices (CCD)



Infrared Cameras

TEC sub-assemblies provide a temperature-controllable, uniform-temperature, high-emissivity surface used in calibrating infrared (IR) detector arrays and FLIR systems. (Infrared Cameras & Thermal Imagers)

http://www.tec-microsystems.com

thermoelectric cooler/heater

koolatron

Koolatron 12 Volt
Coolers and Warmers
heat or cool your lunch and beverages.

“LG Electronics Objet” refrigerator

capacity :40 liters

refrigerating temperature by minimum to 3℃

Seoul, South Korea, Nov. 19th, 2018

LG Innotek

DMD PROJECTOR COOLING MODULE

5000ANSI BX501B TE Cooling Module (LG)

- World first TE cooling module for LG high lumen DMD Projector
- High cooling effectiveness: COP>0.4
- Very low current operation
- Multi heat sources solution
- Supplying since 2008

TED Cup-Holders
Cooling: 0~5C / Heating: 55~65C
Production since May 2014
Hyundai/Kia Motor Company

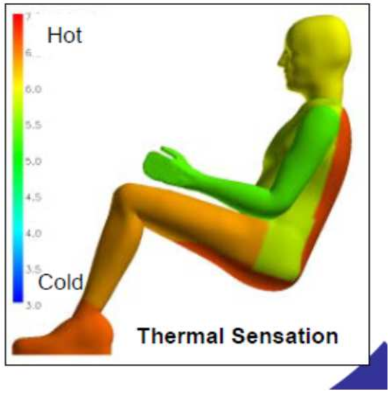
www.tesbiinc.com

watercooler

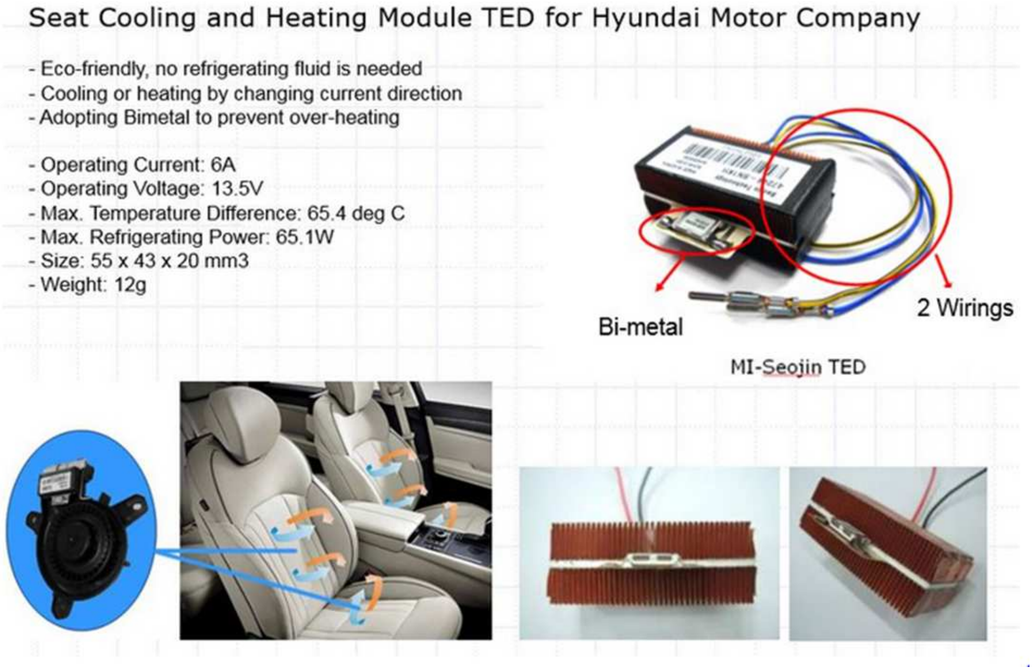
Vehicles cooling and heating

Today’s automotive climate control system exerts a large auxiliary load on the vehicle’s powertrain

Cool locally driver and passenger and not the whole car



Ford group :
Thermoelectric HVAC (Heating, Ventilation and Air-Conditioning)



Seat Cooling and Heating Module TED for Hyundai Motor Company

- Eco-friendly, no refrigerating fluid is needed
- Cooling or heating by changing current direction
- Adopting Bimetal to prevent over-heating

- Operating Current: 6A
- Operating Voltage: 13.5V
- Max. Temperature Difference: 65.4 deg C
- Max. Refrigerating Power: 65.1W
- Size: 55 x 43 x 20 mm3
- Weight: 12g

Sony's New **Wearable 'Air Conditioner'**
Will Keep You From Sweating
Through Your Clothes

Future : refrigeration systems

Vapour compression refrigeration systems have been subject to severe technological modifications due to strict regulations about the working fluids employed

- Safety aspects (toxicity and flammability),
- Environmental issues such as Ozone Depletion and Global Warming.

refrigerant	issue	ODP (Ozone depletion potential)	GPW Global Warming Potential	banned in year
CFC ChloroFluoroCarbures	**impact on the Ozone Layer**			2000
R12		1	10900	
HCFC HydroChloroFluoroCarbures	**impact on the Ozone Layer**			2015
R22		0,055	1810	
HFC HydroFluoroCarbures	**Impact Global Warming**		GPW>2500	January 2020
HFC	Impact Global Warming		GPW>150	January 2022
R404A		0	3900	January 2020
R507A		0	4000	January 2020
R134a : 1,1,1,2-tétrafluoroéthane ;		0	1430	January 2022
other refrigerants				
R744 CO2 (commercial use)	high pressure and low critical temperature, refrigeration systems require special equipment designs.	0	1	high safety level
R717 NH3 (industrial use)	most efficient refrigerant	0	0	Toxicity
R600 Isobutane (commercial use)	domestic and small commercial refrigerators.	0	3	Highly flammable

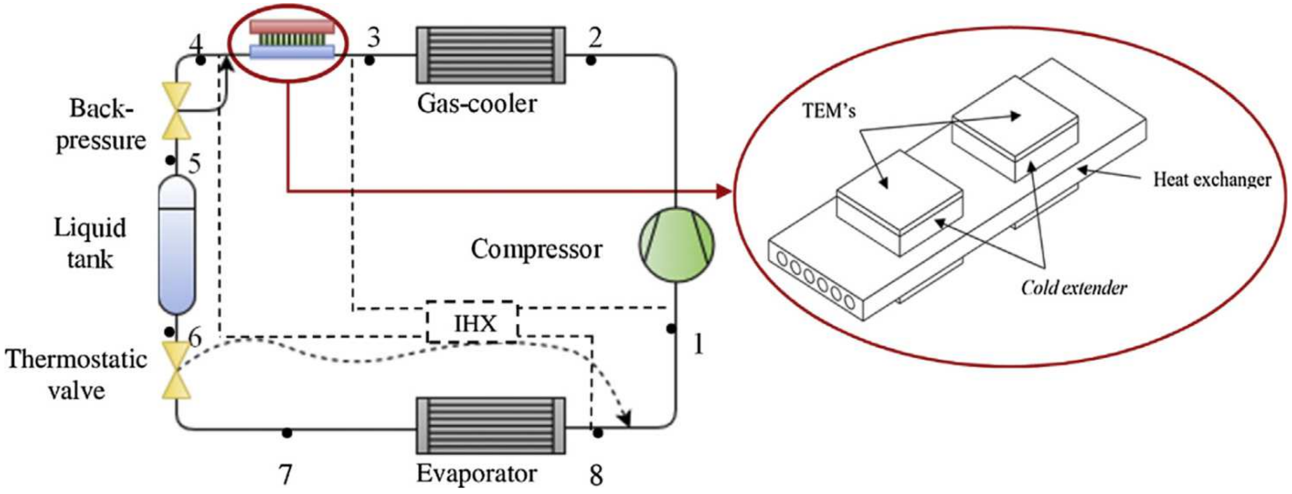
Refrigerants Environmental Data.Ozone Depletion and Global Warming Potential.
Ref LINDE Group http://www.linde-gas.com/en/products_and_supply/refrigerants/

Major difference between R744 (CO2) and other refrigerants : pressure/temperature characteristic.
high pressure and low critical temperature : refrigeration systems require special equipment designs.

Subcooling system is necessary to improve the COP for ambiant temperature > 15°

Research of different systems that could increase the COP of the CO2 plants

Thermoelectric refrigeration subcooling system (TESC) : Improvement up to 33 % in the cooling capacity and up to 24 % in the COP.



D. Astrain et all, Improvements in the cooling capacity and the COP of a transcritical CO2 refrigeration plant operating with a thermoelectric subcooling system, Applied Thermal Engineering, Vol 155, 2019,

Temperature measurements

The temperature is a particular quantity

We can define equality but we can not define the sum of two temperatures

10kg+5kg=15kg

10° + 20° = ?

ITS (International Temperature Scale) T90

Substance and its state	**Defining point T90 K**	**T90 °C**
Triple point of hydrogen	13.8033	-259.3467
Triple point of neon	24.5561	-248.5939
Triple point of oxygen	54.3584	-218.7916
Triple point of argon	83.8058	-189.3442
Triple point of mercury	234.3156	-38.8344
Triple point of water	273.16	0.01
Melting point of gallium	302.9146	29.7646
Freezing point of indium	429.7485	156.5985
Freezing point of tin	505.078	231.928
Freezing point of zinc	692.677	419.527
Freezing point of aluminum	933.473	660.323
Freezing point of silver	1234.93	961.78
Freezing point of gold	1337.33	1064.18
Freezing point of copper	1357.77	1084.62

17 reference points of temperature

2019 New SI

November 2018 revised definitions of the kilogram, ampere, kelvin and mole approved by the General Conference on Weights and Measures (CGPM)

The revised definitions came into force on 20 May 2019

One kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy kT by 1.380649 x 10^{-23} *J.*
Constante de Boltzmann

Can I get my thermometer calibrated in the same way as I did before 20 May 2019?

Yes. The new definition of the kelvin has not impacted the status of the widely-used ITS-90 and PLTS-2000 temperature scales. The Consultative Committee for Thermometry (CCT) has published information concerning immediate and future advantages of the new definition.

www.bipm.org/en/measurement-units/faqs.html

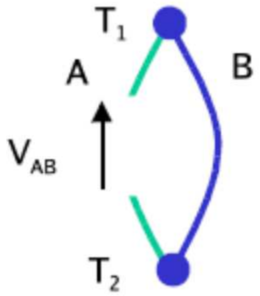
Thermocouples

Thermocouple : a sensor for measuring temperature

It consists of two dissimilar **metals**, joined together.
When the junction of the two metals is heated or cooled a voltage is produced that can be correlated back to the temperature.

V_{AB} is function of:

- Nature of the two metals
- Temperatures T1 and T2



T_1 sensor junction

T_2 reference junction

Table for $T_2 = 0$ and couple A,B $E_{AB}(T_1)$

Thermocouples Type K

Table ITS-90 Thermoelectric Voltage in mV

°C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920

Coefficients of reference equations giving the thermoelectric voltage, E, as a function of temperature, t90 , for the indicated temperature ranges

Temperature below 0°C $E = \text{sum}(i = 0 \text{ à } n)\ c_i{*}t_{90}^{i}$ t_{90} = Temperature (°C) E = Voltage (mV)

Temperature above 0 °C $E = \text{sum}(i = 0 \text{ à } n)\ c_i{*}t_{90}^{i} + a_0{*}e^{a_1(t_{90}-a_2)^2}$

Température (°C)	-270 à 0	0 à 1372
c_0	0	-0.176004136860e-1
c_1	0.394501280250e-1	0.389212049750e-1
c_2	0.236223735980e-4	0.185587700320e-4
c_3	-0.328589067840e-6	-0.994575928740e-7
c_4	-0.499048287770e-8	0.318409457190e-9
c_5	-0.675090591730e-10	-0.560728448890e-12
c_6	-0.574103274280e-12	0.560750590590e-15
c_7	-0.310888728940e-14	-0.320207200030e-18
c_8	-0.104516093650e-16	0.971511471520e-22
c_9	-0.198892668780e-19	-0.121047212750e-25
c_{10}	-0.163226974860e-22	
a_0		0.1185976
a_1		-0.1183432e-3
a_2		0.1269686e+3

coefficients of approximate inverse functions giving temperature, t90 , as a function of the thermoelectric voltage, E, in selected temperature and voltage ranges.

$$T_{90} = c_0 + c_1E + c_2E^2 + c_3E^3 + c_4E^4 + \dots + c_nE^n$$

Température (°C)	-200 à 0	0 à 500	500 à 1372
Tension (mV)	-5.891 à 0.000	0.000 à 20.644	20.644 à 54.886
c_0	0	0	-1.318058E+02
c_1	2.5173462E+01	2.508355E+01	4.830222E+01
c_2	-1.1662878E+00	7.860106E-02	-1.646031E+00
c_3	-1.0833638E+00	-2.503131E-01	5.464731E-02
c_4	-8.9773540E-01	8.315270E-02	-9.650715E-04
c_5	-3.7342377E-01	-1.228034E-02	8.802193E-06
c_6	-8.6632643E-02	9.804036E-04	-3.110810E-08
c_7	-1.0450598E-02	-4.413030E-05	0
c_8	-5.1920577E-04	1.057734E-06	0
c_9	0	-1.052755E-08	0
Erreur (°C)	-0.02 à 0.04	-0.05 à 0.04	-0.05 à 0.06

http://srdata.nist.gov/its90/main/

Thermocouples

Letter-designation for Thermocouples.	Alloy	Domaine de la table en °C
K	Nickel-chromium alloy(+)/Nickel-aluminium alloy(-)	-270 to 1370 °C
T	Copper(+)/Copper-nickel alloy(-)	-270 to 400 °C
J	Iron(+)/Copper-nickel alloy(-)	-210 to 1200 °C
N	Nickel-chromium-silicon alloy(+)/Nickel-silicon alloy(-)	-270 to 1300 °C
E	Nickel-chromium alloy(+)/Copper-nickel alloy(-)	-270 to 1000 °C
R	Platinum13%Rhodium(+)/Platinum(-)	-50 to 1760 °C
S	Platinum10%Rhodium(+)/Platinum(-)	-50 to 1760 °C
B	Platinum30%Rhodium(+)/Platinum6%Rhodium(-)	0 to 1820 °C
G (Not Official Symbol or Standard)	Tungsten / Tungsten 26% Rhenium	1000 to 2300 °C
C (Not Official Symbol or Standard)	Tungsten 5% Rhenium / Tungsten 26% Rhenium	0 to 2300 °C
D (Not Official Symbol or Standard)	Tungsten 3% Rhenium / Tungsten 25% Rhenium	0 to 2400 °C

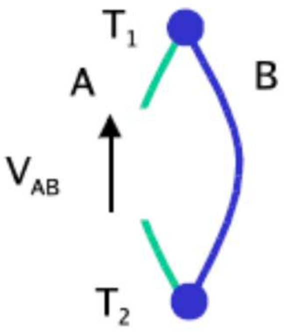
Standard IEC 584.1 (1995) IEC - International Electrotechnical Commission

- IEC 60584-1 Thermocouple reference tables - E = f(T) e.m.f.-temperature relationships
- IEC 60584-2 Tolerances
  - This standard contains the manufacturing tolerances for both noble and base metal thermocouples manufactured in accordance with e.m.f.-temperature relationships of Part 1 of the standard.
- IEC 60584-3

  Thermocouples - : Extension and compensating cables - Tolerances and identification system

Thermocouples

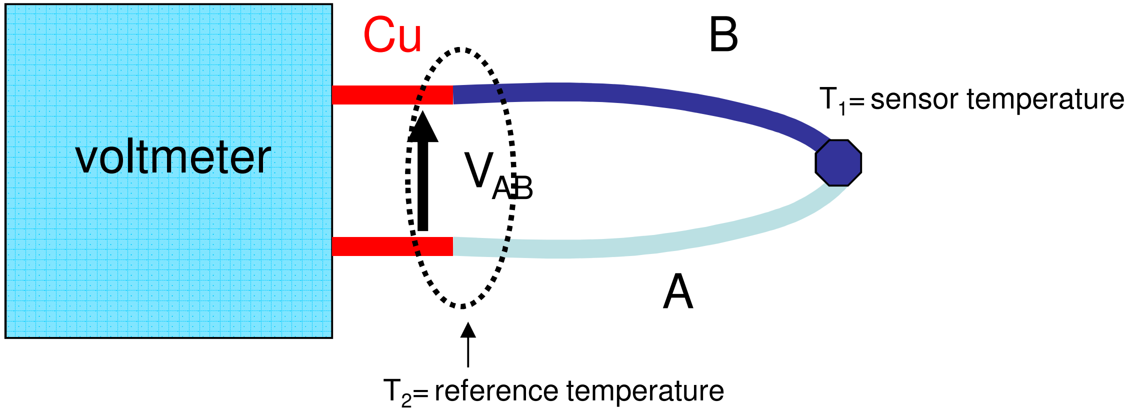
Cold junction compensation



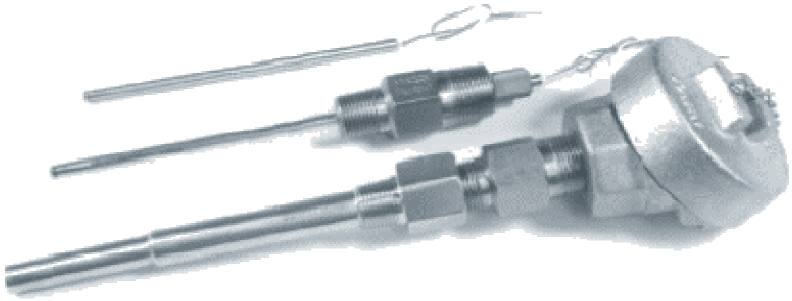
Thermocouples measure the temperature difference between two points, not absolute temperature

$$E(T_1)=V_{AB} + E(T_2)$$

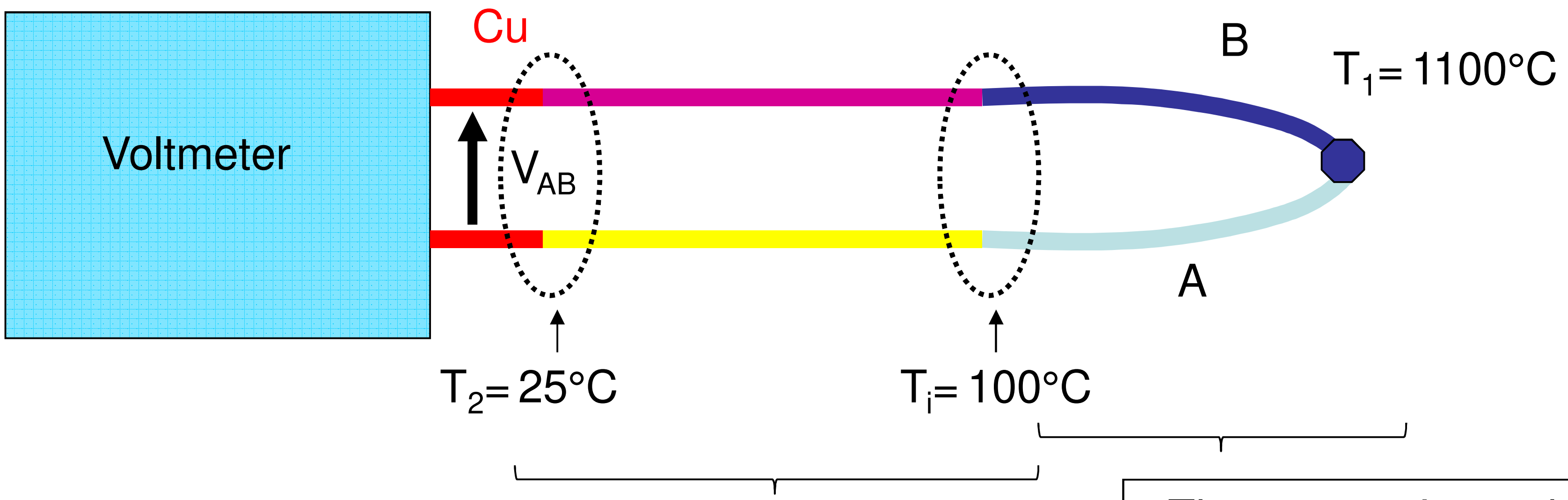
industrial thermocouples



* T°maxi: 450°C



Thermocouples : Extension Wire



Extension grade wire is only used to extend a thermocouple signal from a probe back to the instrument reading the signal. The extension grade wire (or sheath) typically will have a lower ambient temperature limit in which the wire may be used

Cheap

Thermocouple grade wire is wire that is used to make the sensing point (or probe part) of the thermocouple.

Expensive

Thermocouples : Properties

sensitivity

Thermocouple Type	Seebeck Coefficient at 25°C (µV/°C)	Sensitivity for 0.1°C (µV)
E	**61**	**6.1**
J	**52**	**5.2**
K	**40**	**4.0**
R	**6**	**0.6**
S	**6**	**0.6**
T	**41**	**4.1**

Measurement system with high resolution and quality

Sensors are very sensitive to electric noises

Advantages

- Large measuring range
- robust
- Many forms
- Response time
- Cost

Disadvantages

- Decalibration (oxidation ...)
- Sensitivity to electrical noise