ALLIANCE
FOR GREEN HEAT
low carbon, renewable and local

BTEC
Biomass Thermal Energy Council

Thermoelectric Wood Stoves

Thursday, September 21, 2017
10:00 AM ET

In support of the Alliance for Green Heat's 4th Wood Stove Competition in November 2018

NEXT GENERATION
WoodStove
DesignChallenge

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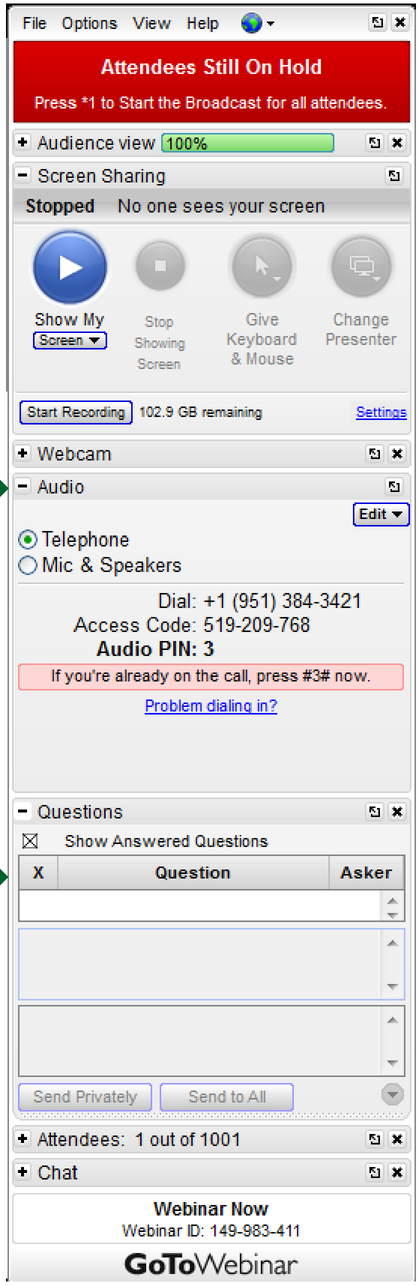
Audio

Questions



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Webinar Now
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ALLIANCE
FOR GREEN HEAT
low carbon, renewable and local

- ✓ 501c3 nonprofit
- ✓ Promotes clean & efficient biomass heaters
- ✓ National voice for wood heat consumers
- ✓ Hosts design competitions
- ✓ Encourages transparency from manufacturers and regulators

NEXT GENERATION WoodStove DesignChallenge

- 4th Wood Stove Design Challenge
  - November 9-14, 2018
  - National Mall in Washington DC
- Two Competition Categories:
  - Automated stoves
  - Thermoelectric stoves

Thank you!

John Ackerly – jackerly@forgreenheat.org

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(for thermoelectric issues)

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WoodStove
DesignChallenge

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About BTEC

The national trade association for the modern wood heating industry.

- Engage in technical codes and standards development, public advocacy, and education.

- **100+ members and associates across the US and Canada:**
- Fuel Producers
- Manufacturers
- Sellers
- Installers
- Service Providers
- Universities
- Non-profits & NGOs
- Government agencies

Bear Mountain Forest Products
SINCE 1988

CENTRAL BOILER

Forest Energy Corporation

NEW ENGLAND
Premium Wood Pellets
made from 100% wood
WOOD PELLET, LLC

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alphabet energy

we make waste heat valuable

Adam Lorimer, Co-Founder

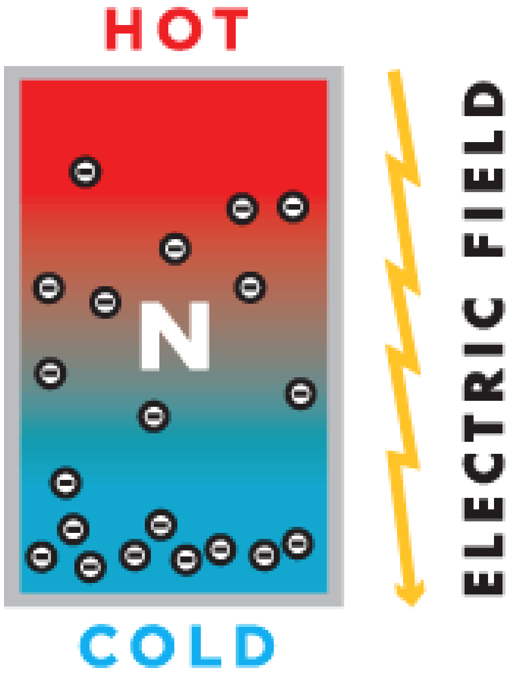
September 2017 adam@lorimer-intl.com

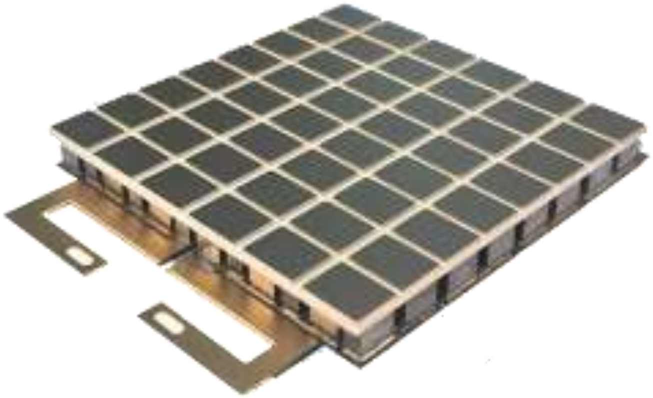
Agenda

- What is a Thermoelectric?
- What can you do with it?
- How do you do it?

What is a Thermoelectric?

Materials that directly turn heat into electricity with no moving parts





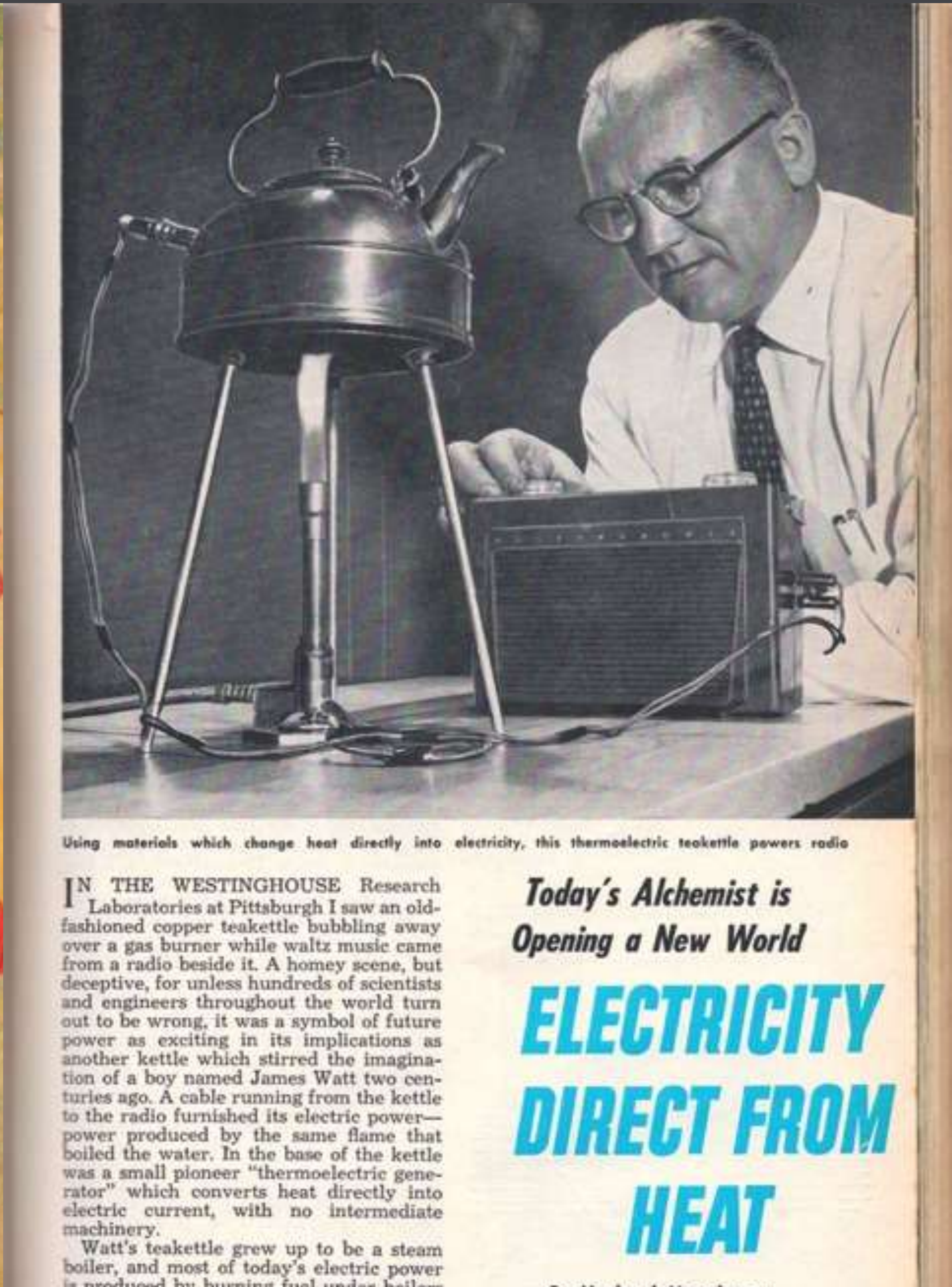
MAY 1959 REPORT ON LARK AND RAMBLER 35 CENTS

POPULAR MECHANICS MAGAZ

WRITTEN SO YO

Bail Out for Fun
—page 65

BUY THE RIGHT
POWER MOWER



Using materials which change heat directly into electricity, this thermoelectric teakettle powers radio

Today's Alchemist is Opening a New World

ELECTRICITY DIRECT FROM HEAT

IN THE WESTINGHOUSE Research Laboratories at Pittsburgh I saw an old-fashioned copper teakettle bubbling away over a gas burner while waltz music came from a radio beside it. A homey scene, but deceptive, for unless hundreds of scientists and engineers throughout the world turn out to be wrong, it was a symbol of future power as exciting in its implications as another kettle which stirred the imagination of a boy named James Watt two centuries ago. A cable running from the kettle to the radio furnished its electric power—power produced by the same flame that boiled the water. In the base of the kettle was a small pioneer "thermoelectric generator" which converts heat directly into electric current, with no intermediate machinery.

Watt's teakettle grew up to be a steam boiler, and most of today's electric power

The Alphabet Energy E1™

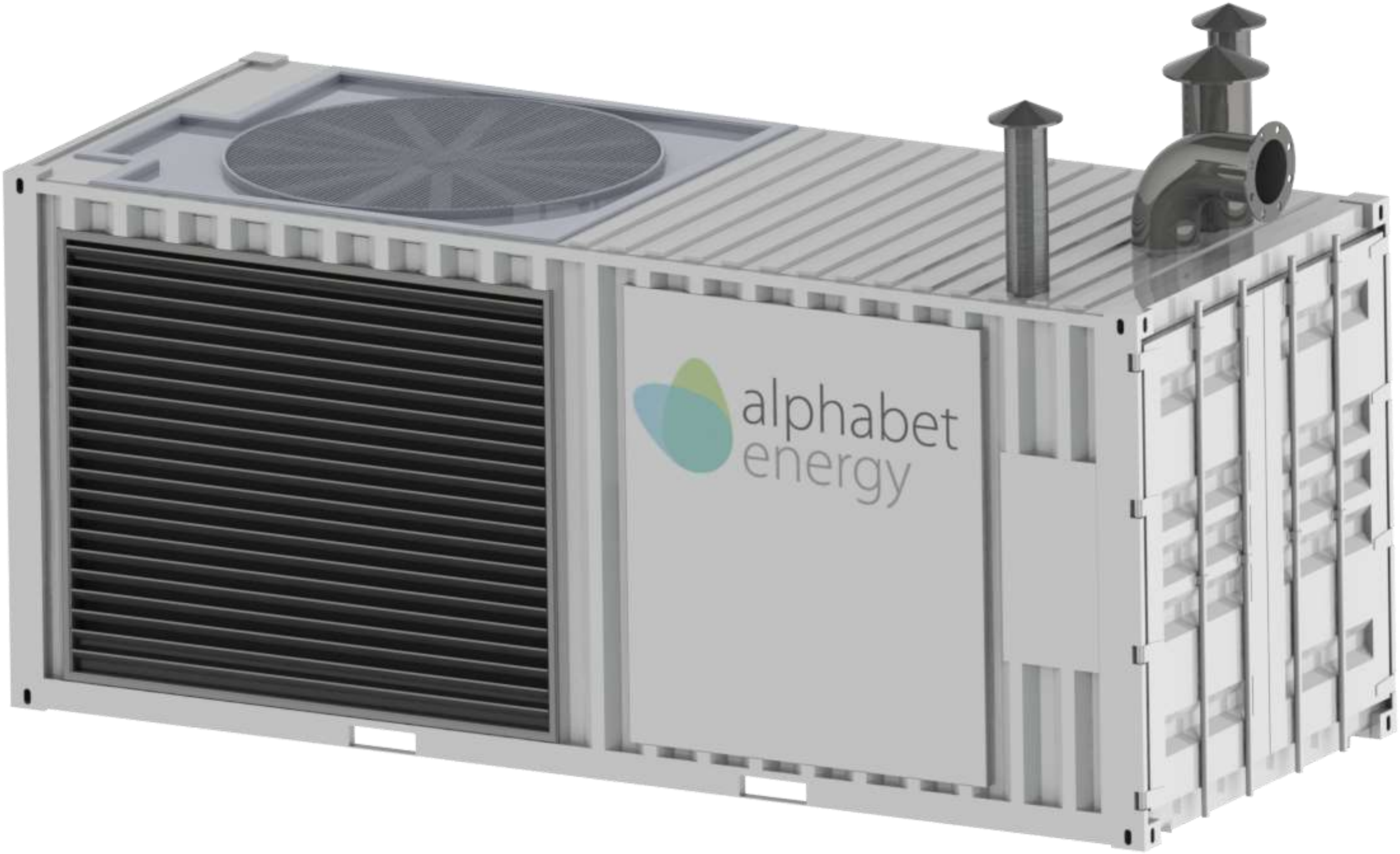
Heat Recovery for MW Diesel & Nat Gas Engines in Remote Service

15 kW demonstrated output in the field – most powerful thermoelectric generator ever built

The Alphabet Energy E1™ Thermoelectric Generator

The Alphabet Energy E1™ in the Eagle Ford, Texas

E1 Gen III – 25kW in development



1st Commercial Thermoelectric Product > 1kW The Power Generating Combustor - PGC

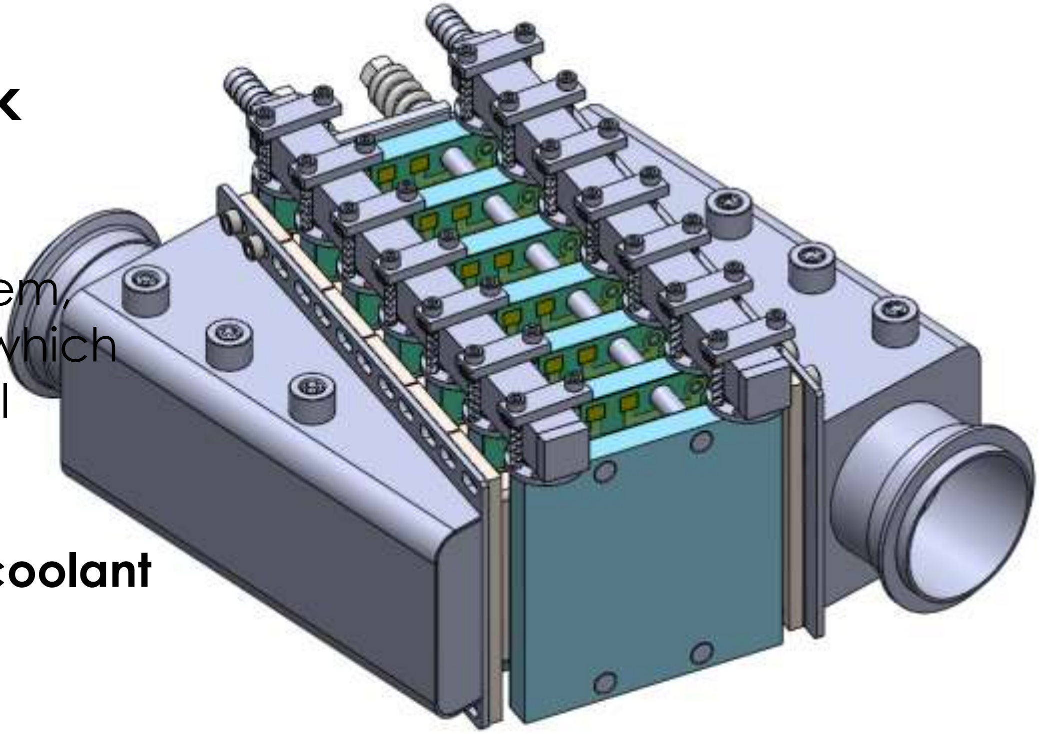
- **2.5kW Net Power (5kW Gross)**
- **Quad-O combustion efficiency**
- **Power for instruments, communications, cathodic protection, etc**
- **Powers air compressor to eliminate gas hydraulics**
- **Permitted as a generator not a flare.**

Automotive PowerModule

350W Peak power on a 5.3L truck
155W Average City & Highway.

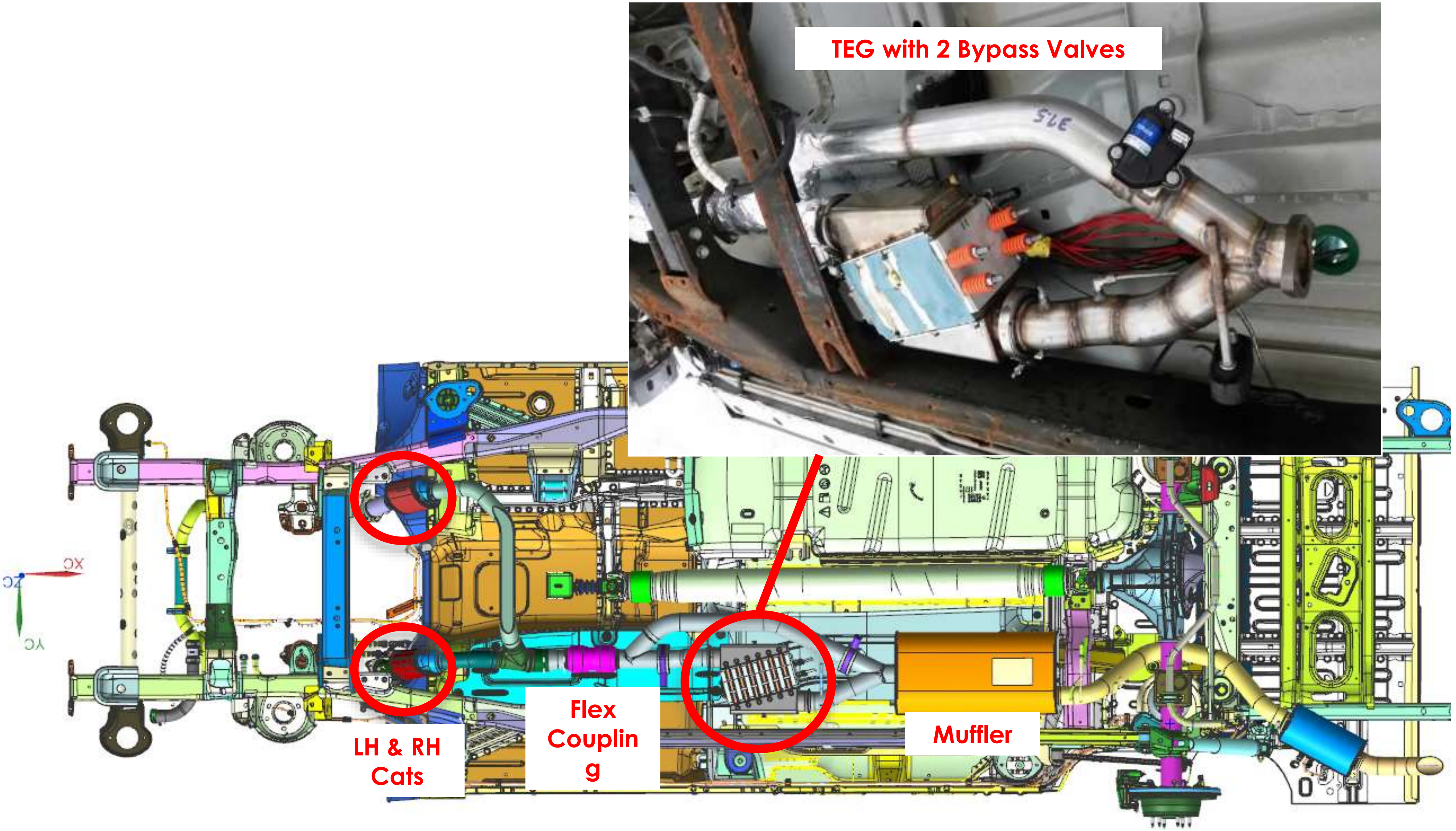
The PowerModule fits in the exhaust system, extracting heat and generating power which unloads the alternator and improves fuel economy.

Transferring exhaust heat to the engine coolant accelerates warm-up and further boosts efficiency



3% fuel economy improvement,
A key technology in satisfying 2025 CAFE standards

Vehicle Integration Test 5.3L Suburban


TEG with 2 Bypass Valves

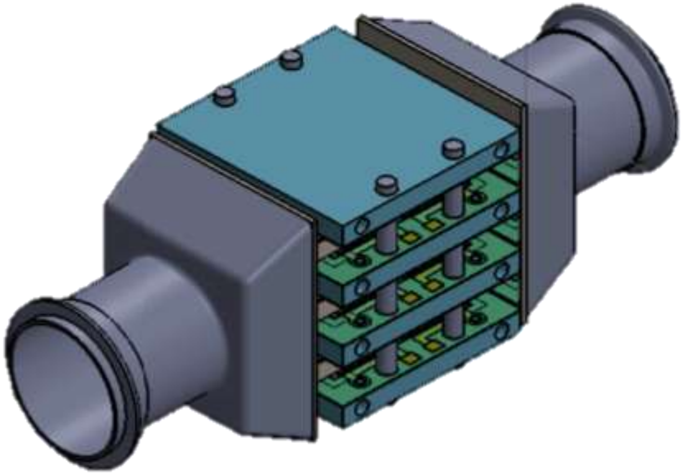
LH & RH Cats

Flex Coupling

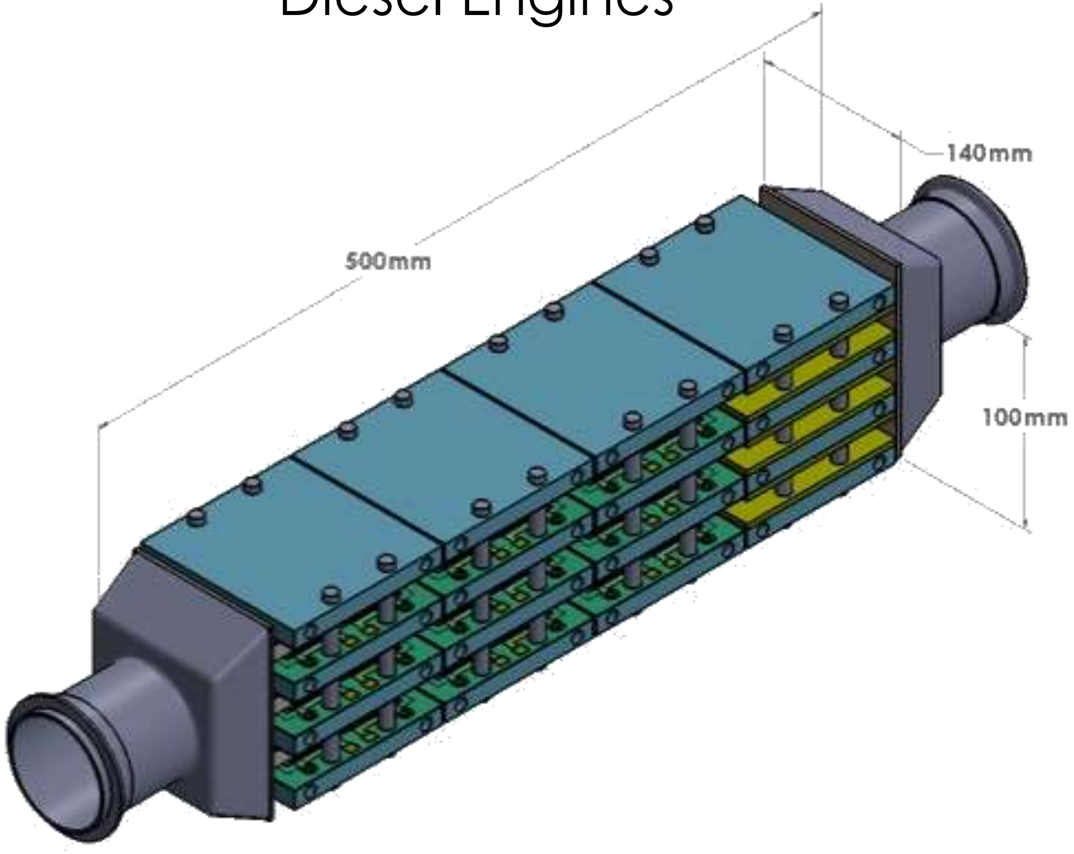
Muffler

Scalable Automotive Architecture

- Units for smaller engines



- Exhaust Gas Recirculation Cooler on Diesel Engines



Practical Thermoelectric Design Issues

1. Thermoelectric Material Selection
2. Thermal Interfaces
3. Thermal Resistance Matching
4. Power Conditioning

Material Selection

Lead Telluride **Half Heusler** **Skutterudite** **LAST**

- High Temperature operation
- High efficiency
- Expensive Raw Materials - commercial dead-end for large volume applications.
- Require Vacuum.
- Not commercially available

Tetrahedrite / MgSi

- AE Material
- Medium-high temperature operation
- High efficiency
- Abundant raw materials - Low cost at scale.
- Operates in air
- Production all committed.

Bismuth Telluride

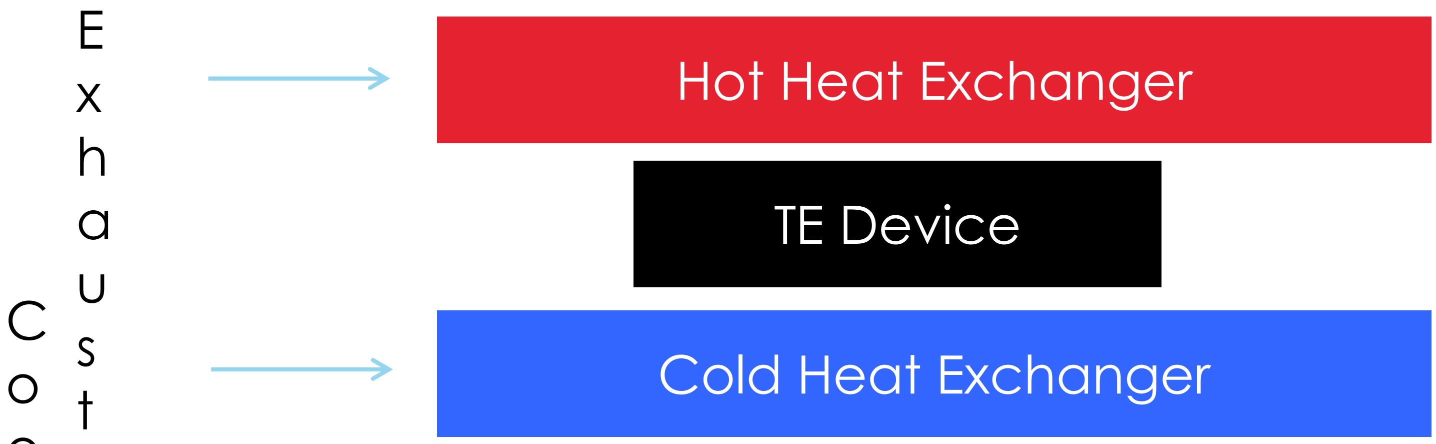
- Low-Medium temperature operation
- Lower power than others
- Operates in air
- Commercially available
- Your only real option.

Marlow - highest power, reliability & cost.
Alternatives: **Tellurex, Ferrotec, Thermonamics**

Performance may vary – datasheets rarely accurate

250C max operating condition, some suppliers quote 300C but this is usually due to poor thermal contact and won't yield benefits.

Putting it together



Exhaust

Cooling Fluid

Hot Heat Exchanger

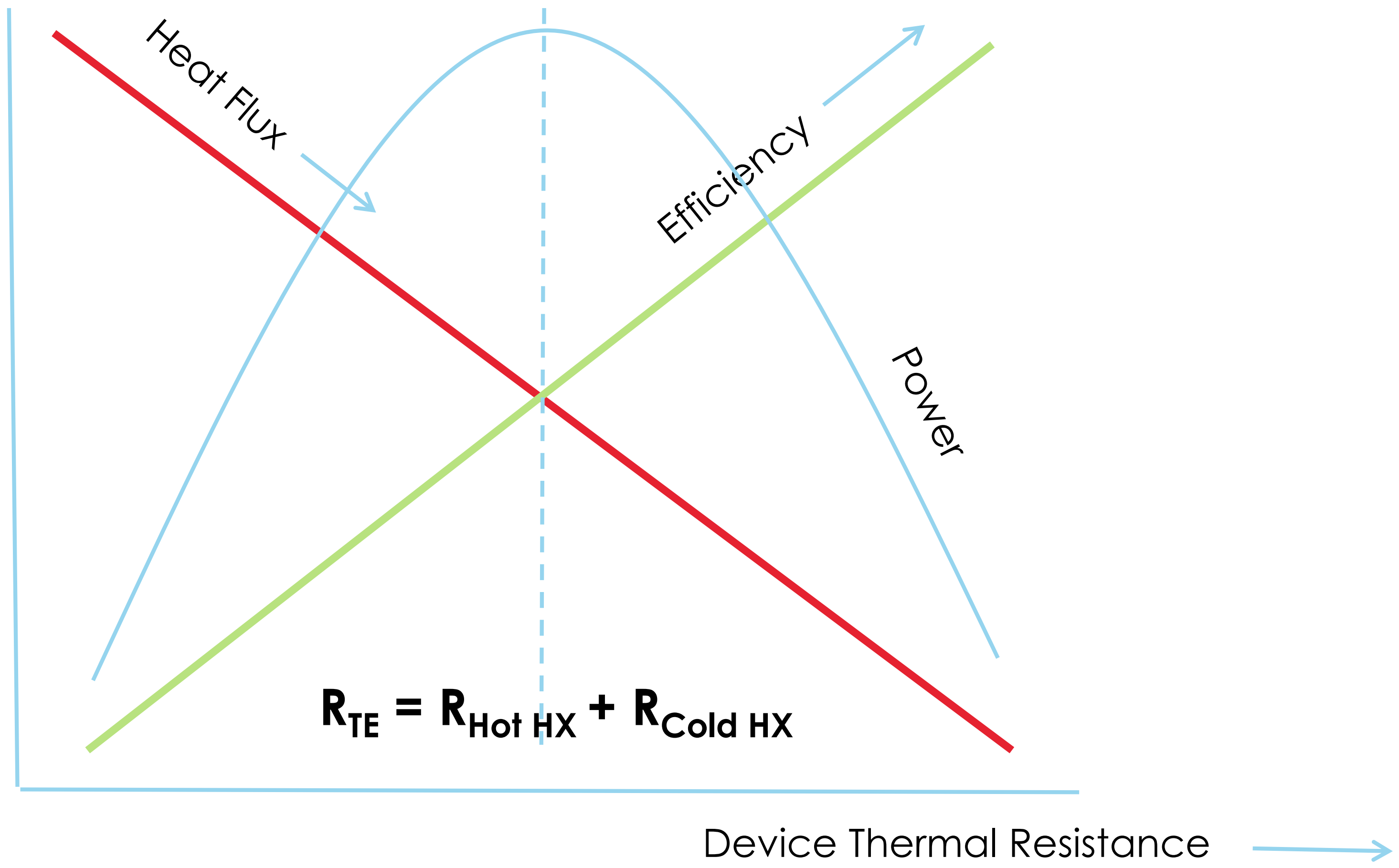
TE Device

Cold Heat Exchanger

- Getting good thermal contact between heat exchanger and TE device while minimizing thermal stress is essential
- Thermal Interface Materials
  - Graphite – up to ~400C, not dielectric, a lot of pressure
  - Thermal Grease – 200C ish, dry out & pump out
  - Silicone Gap Pad – 200C ish, bubbles
- Careful of thermal bypass losses

Thermal Resistance Matching

Efficiency a Device Temperature Gradient

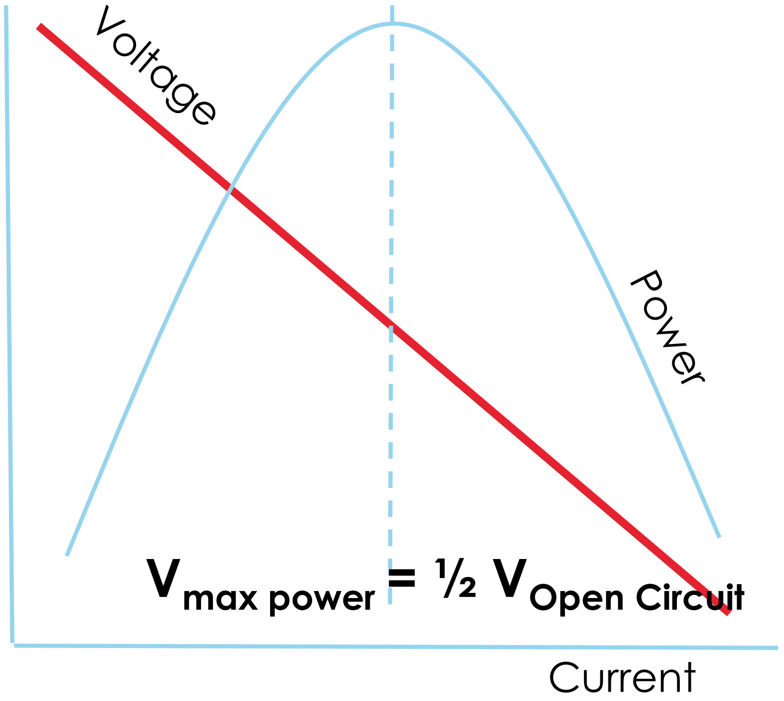


$R_{TE} = R_{Hot\ HX} + R_{Cold\ HX}$

This means half your temperature drop is across the TE (unless limited by operating temp)

Power Conditioning

- Power Output is DC
- Requires Max Power Point Tracking
- Voltage & Current will vary with temperature and flow
- May not be the voltage you want.



$V_{\text{max power}} = \frac{1}{2} V_{\text{Open Circuit}}$

- For DC-AC Power Solar Inverters work with Thermoelectrics
  - Be careful of dielectric strength
- For DC-DC Linear Technologies make a demo-board

Available to consult:

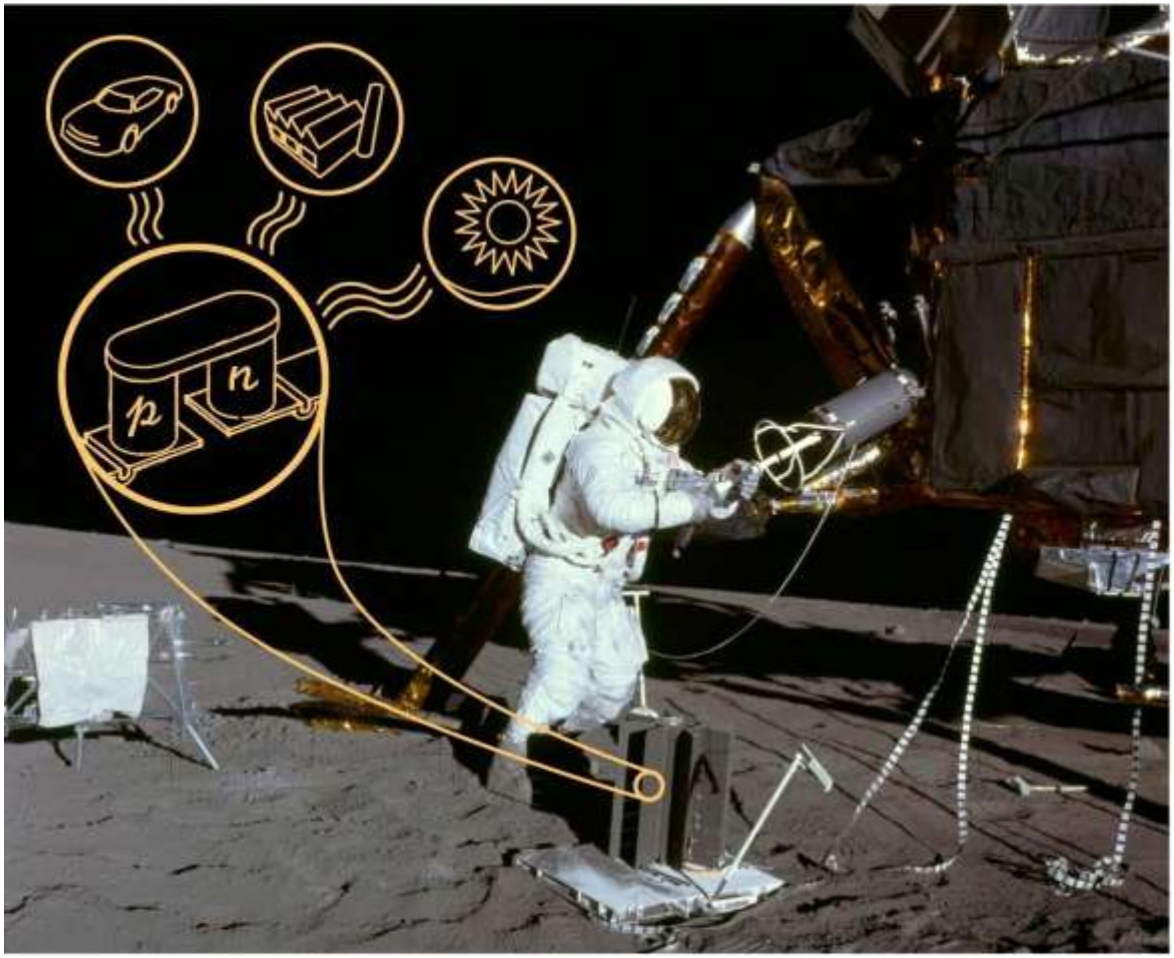
adam@lorimer-intl.com

925 408 1812

Design and Engineering of Thermoelectric Devices

G. Jeffrey Snyder, Northwestern University

http://thermoelectrics.matsci.northwestern.edu



Thermoelectric Device

Thermoelectrics

Convert Heat into Electricity

Heat Flow drives free electrons and holes from hot to cold

Voltage Produced

Seebeck effect

or Thermoelectric Power

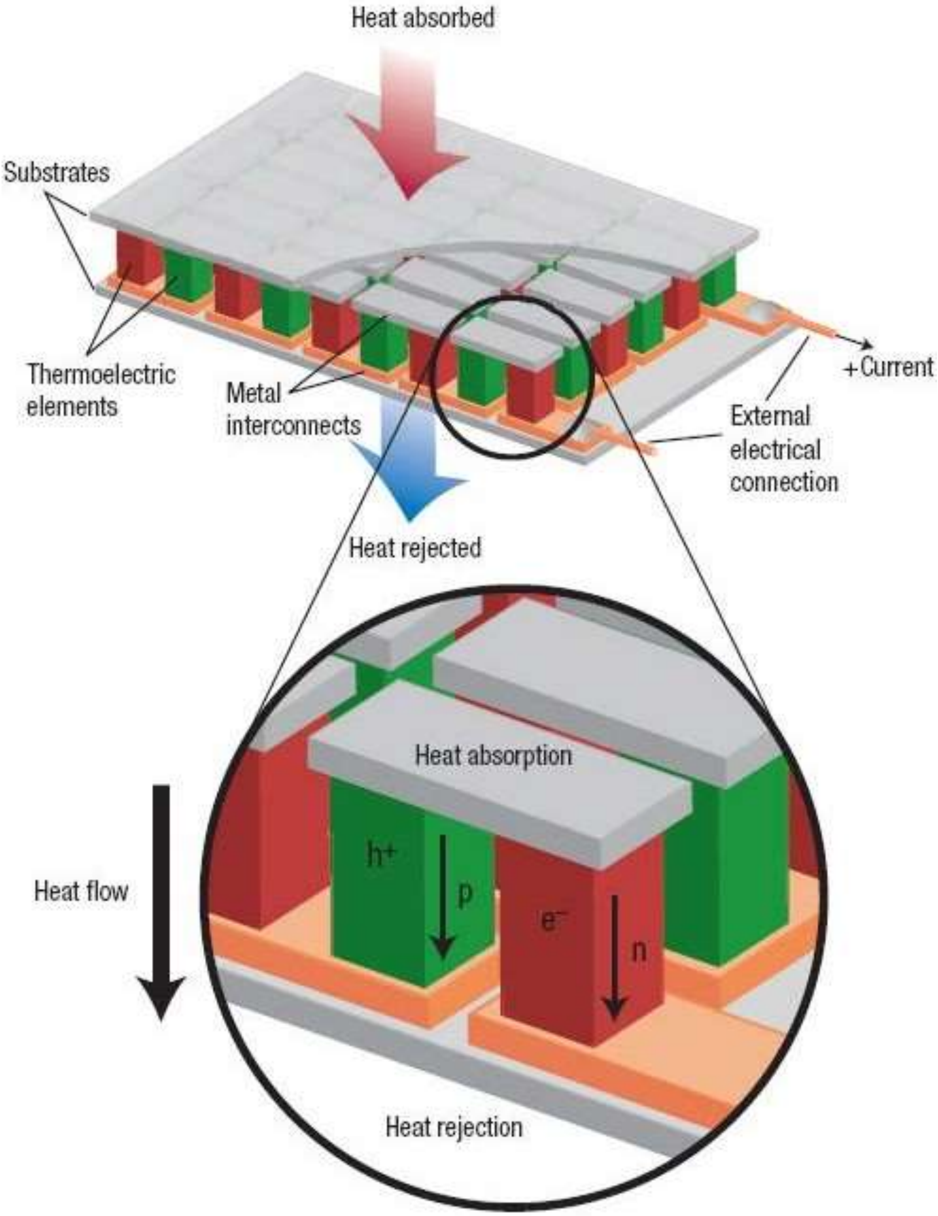
$$V = S \otimes T$$

Seebeck Coefficient α

Efficiency $\sim zT$

$$zT = \frac{S^2}{\rho\kappa} T$$

Typically $zT < 1$



Snyder, Toberer *Nature Materials* **7,** 105 (2008)

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Thermoelectric Applications

Solid State Advantage

- No moving parts
- No maintenance
- Long life
- Scalability

Cooling - Thermal Management

- Small Refrigerators
- Optoelectronics
- Electric Vehicles
  - Zonal HVAC

Power Generation (heat to electricity)

- Spacecrafts
  - Voyager over 40 years!
- Remote power sources

Energy Harvesting

- Remote Sensor Power

2012 Mars Rover *Curiosity*

Gentherm Zonal HVAC

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Co-Generation

Combined Heat and Power

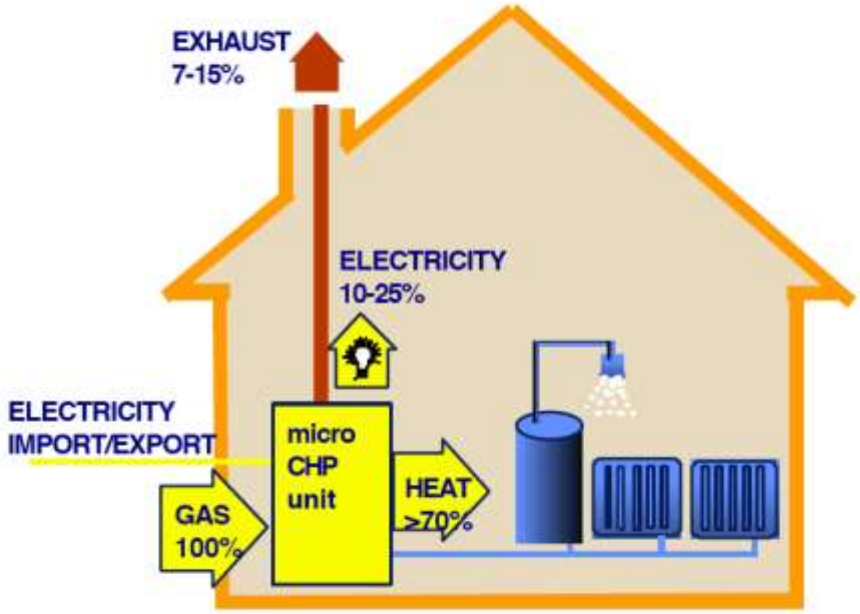
- Burn Fuel to produce Heat
- Convert Heat to Electricity
- Utilize waste Heat for heating

Common for institutional power pla n

- Universities
- Factories
- Where efficiency is valuable
  - 10% of Europe electricity is cogen

Could be used anywhere high exergy content fuel is used for heating

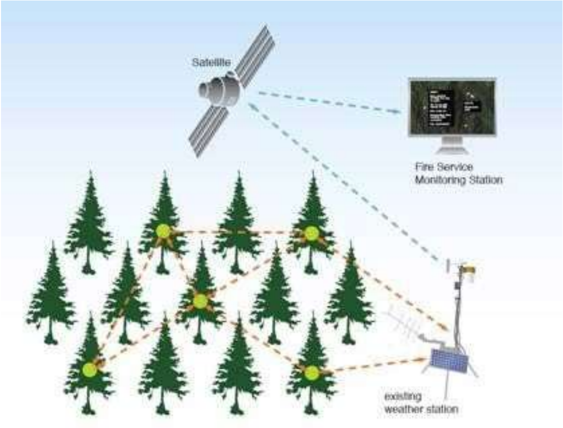
- ~90% efficiency in Electricity Generation
- Capital, Maintenance cost is primary issue



Thermoelectric Energy Harvesting

Situations where replacing a Battery is insufficient

- Li-ion ~ 1kJ/cm^3
- 10% charge loss/month ~ 40µW/cm^3
- one day recharge ~ 10 mW/cm^3



Examples

- Remote Sensors, communications
  - Low average power consumption
- Wearable electronics

Ambient Energy source available

- Light (PhotoVoltaic)
- Vibration
- Heat (ThermoElectric)

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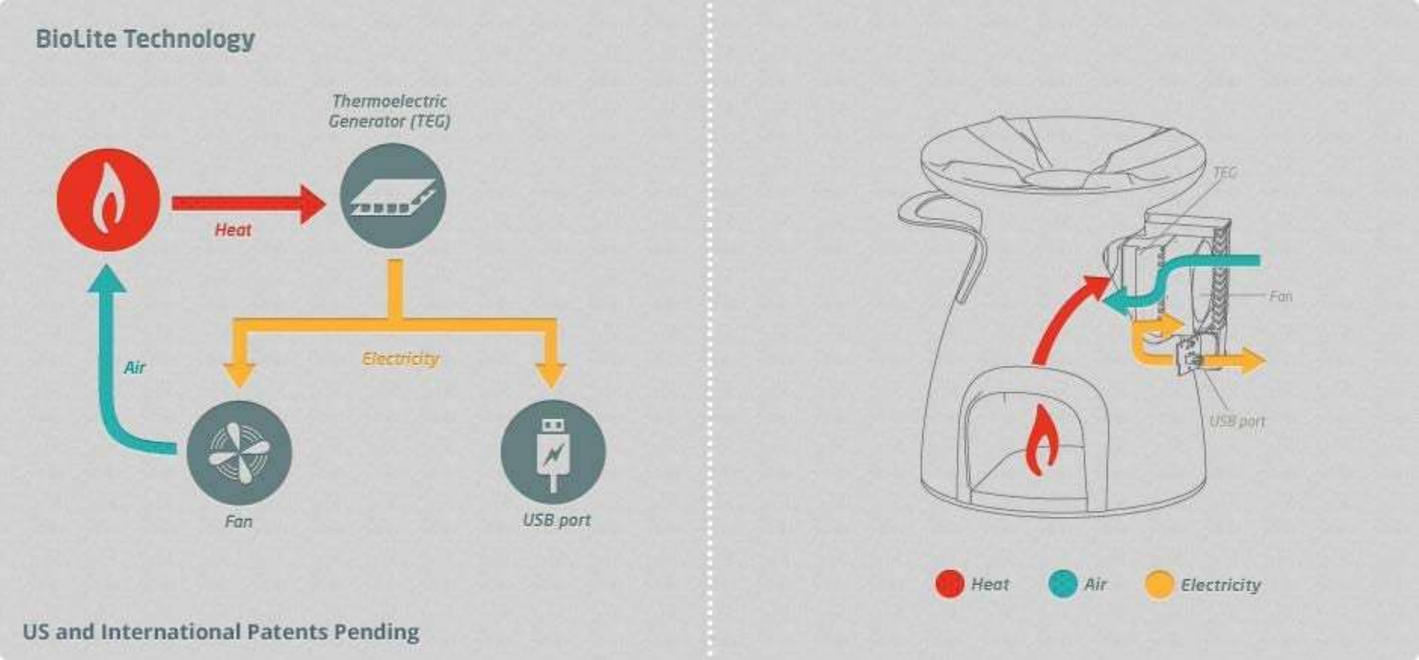
Thermoelectric Stove

Waste heat – Cogeneration example

Thermoelectric powered fan improves combustion

- 95% less smoke (CO), pollution
- 50% less fuel
- recharges cell phone, LED lights.



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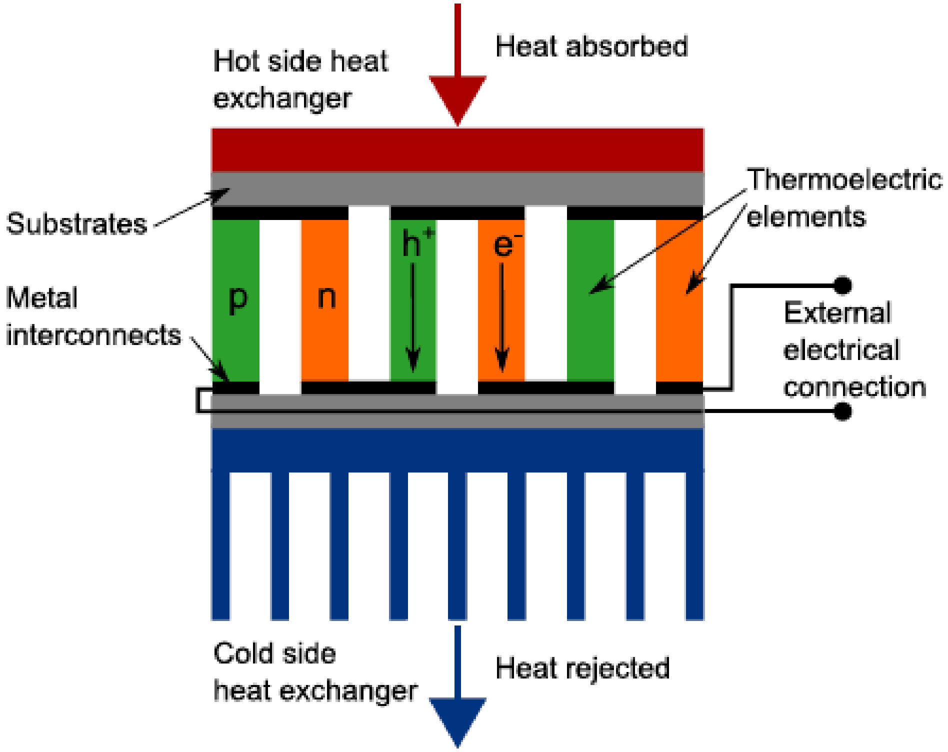
http://biolitestove.com

Conceptual Design of Thermoelectric Generators



Energy Laws

1st law of thermodynamics

Energy is Conserved

2nd law of thermodynamics

Entropy ≥ 0

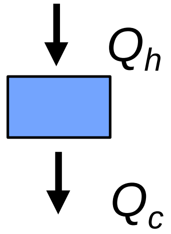
Example 1: Heat Conduction

$Q_h = Q_c$ *(1st law)*

$T_h > T_c$ *(2nd law)*

Heat flows from Hot to Cold

(Unless there is work being done to system)



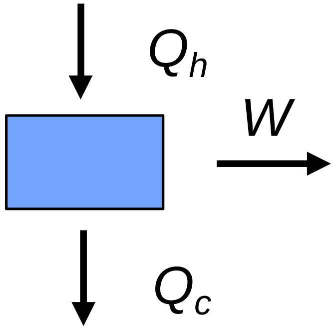
Example 2: Heat Engine

$Q_h = Q_c + W$ *(1st law)*

Efficiency $\eta = W/Q_h$

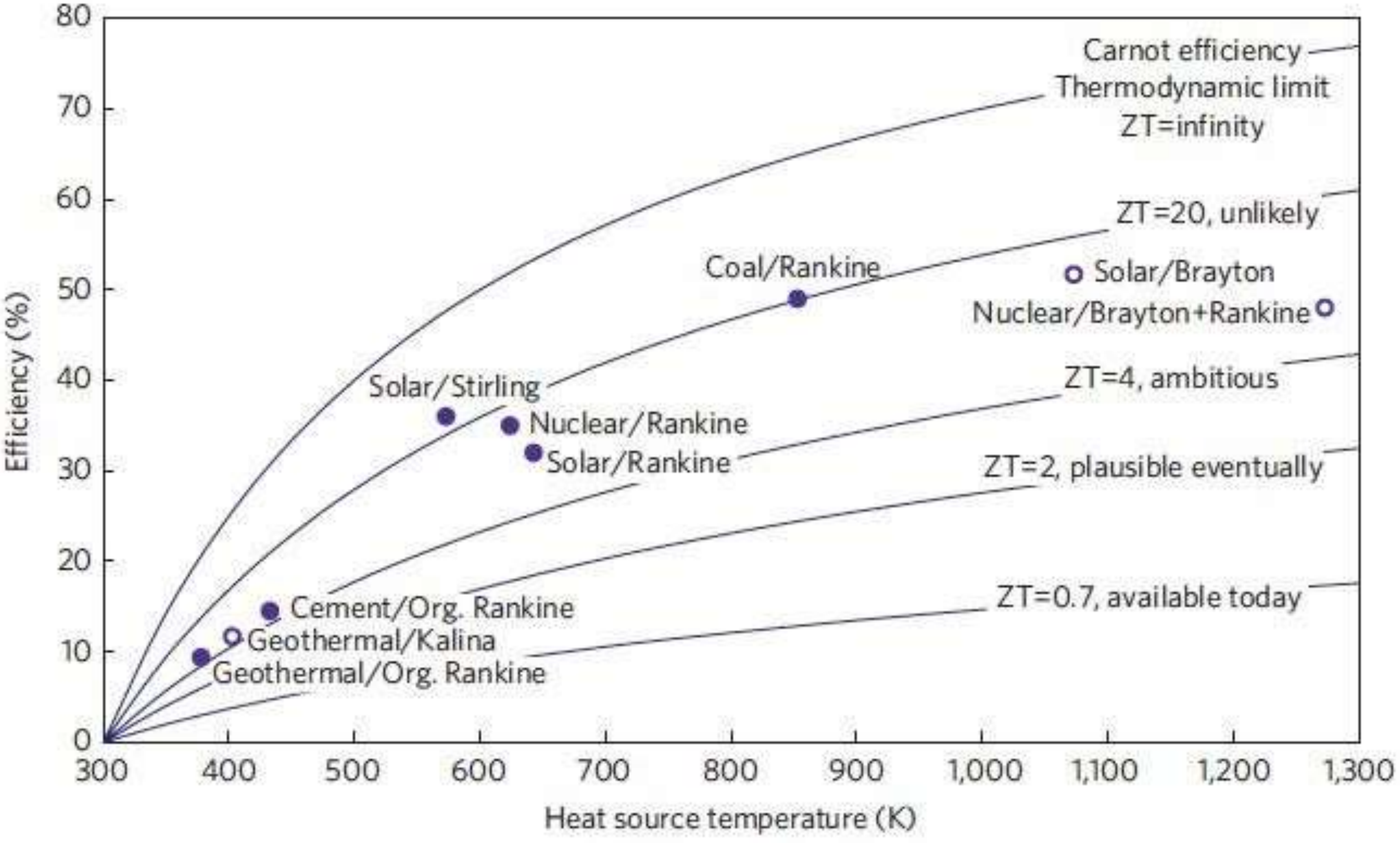
$\eta \leq \Delta T/T_h$ *(Carnot Efficiency)*

Efficiency always less than Carnot



Device Figure of Merit ZT

Efficiency of Thermal to Electric Energy Conversion

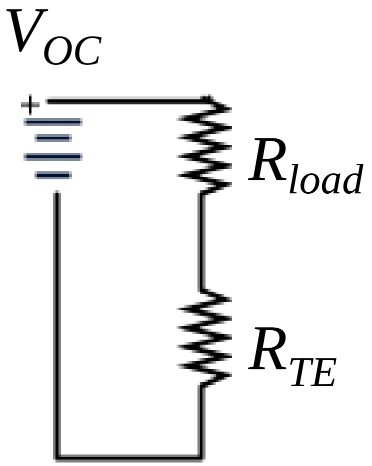


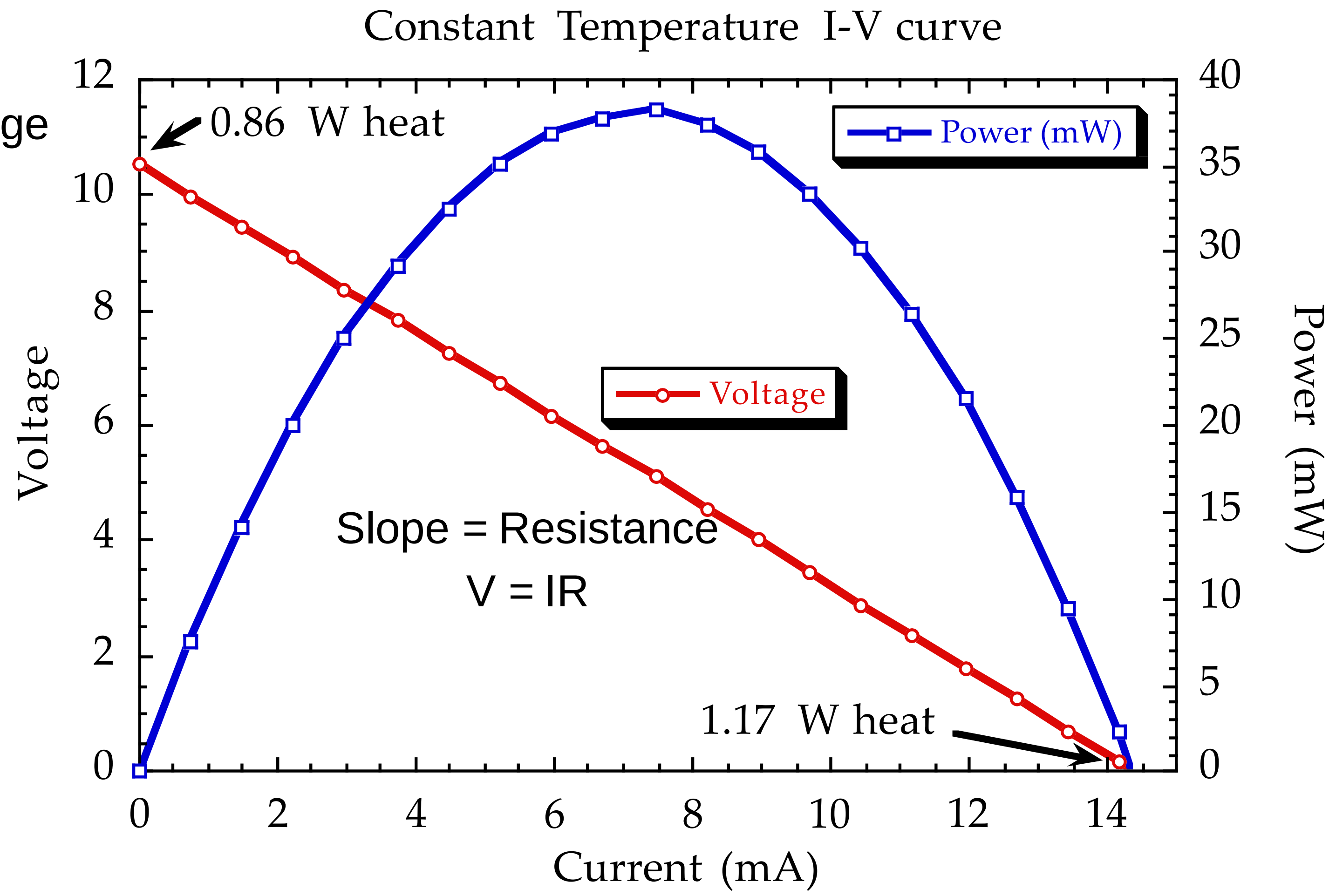
Vining, *Nature Materials* ***8*****,** 83 (2009)

TE Module Electrical Output

Open Circuit Voltage

$V_{OC} = S\Delta T$



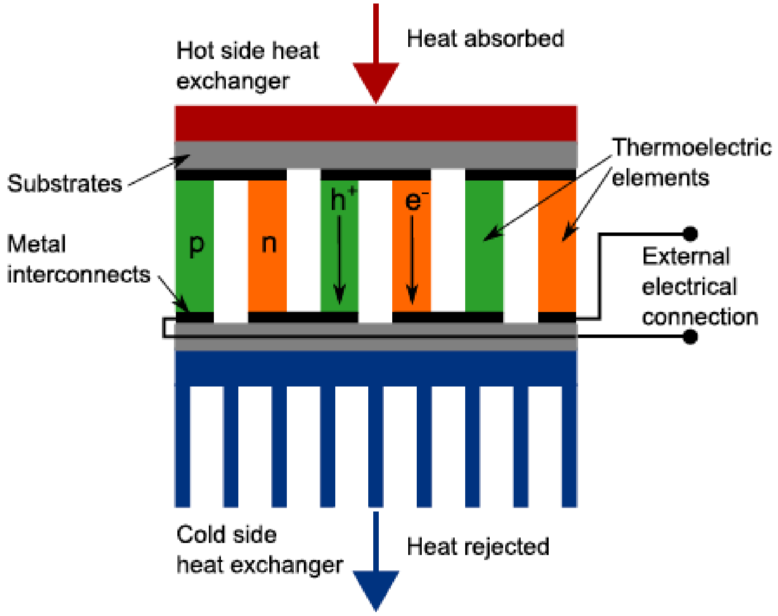


Slope = Resistance

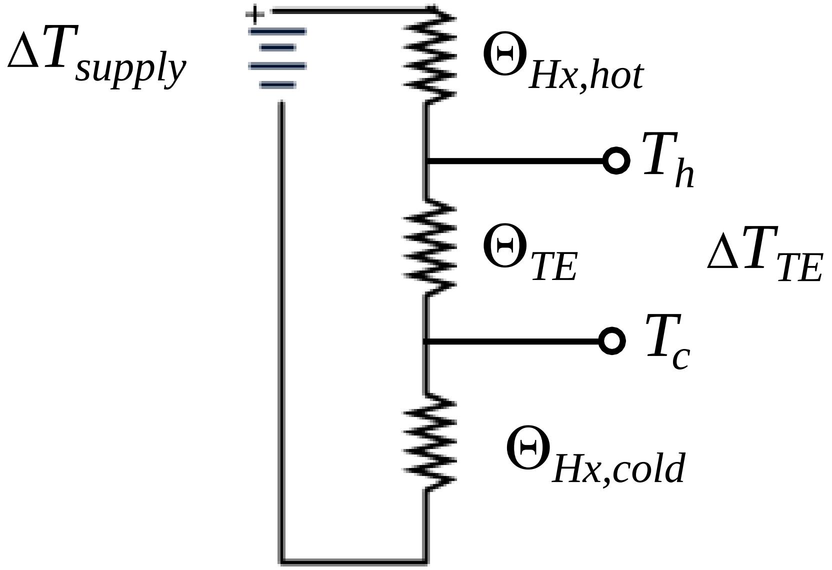
V = IR

Effective Thermal Model

Thermal model



Thermal Circuit



Baranowski, Snyder et al, *J Applied Phys.* 113, 204904, (2013)

Maximizing Power

Thermal Impedance Match

maximum power when

$$\Theta_{TE} = \Theta_{\text{Hx}}$$

so Heat exchangers determine heat flux

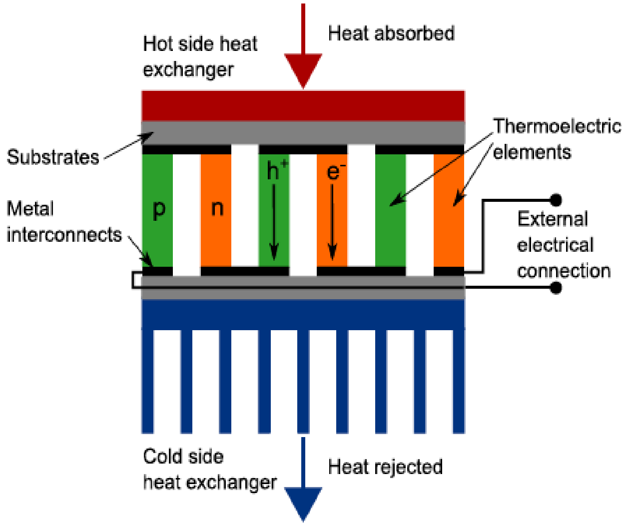
$$\dot{Q} = \frac{\otimes T_{\text{supply}}}{\Theta_{\text{Hx}} + \Theta_{TE}}$$

Efficiency determines power

$$P = \eta \dot{Q}$$

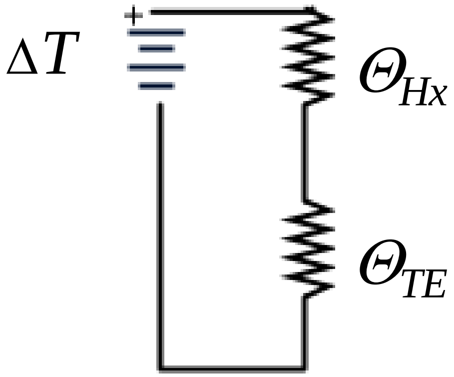
ZT determines efficiency

$$P_{\max} = \frac{\Delta T^2}{4T_h \Theta_{Hx}} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h}$$



Thermal circuit model

$$\Theta_{\text{Hx}} = \Theta_{\text{Hx,hot}} + \Theta_{\text{Hx,cold}}$$



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Baranowski, Snyder et al, J Applied Phys. 113, 204904, (2013)

Device Efficiency from *ZT*

Device Figure of Merit *ZT*

$$\eta = \frac{\otimes T}{T_h}\,\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h}$$

Carnot Factor

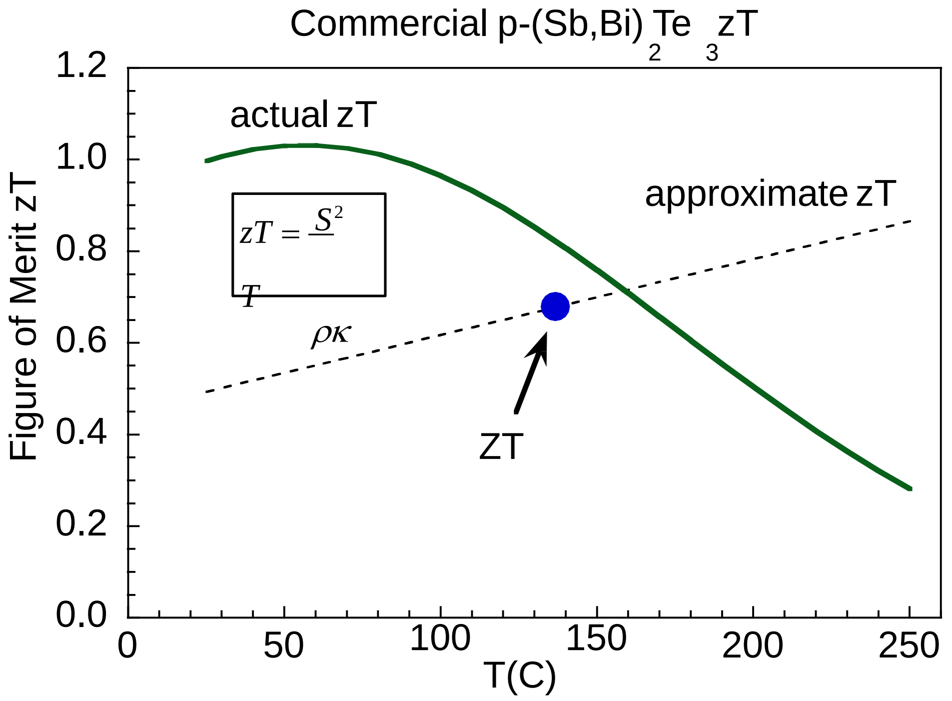
Reduced Efficiency

Seebeck Coefficient S

Electrical Resistance R

Thermal Conductance K

$$ZT \approx \frac{S^2}{RK}\,\frac{T_c+T_h}{2}$$



Device *ZT* is approx. an average of Materials figure of merit *zT* over the temperature range of use

Goldsmid, H. J. Applications of Thermoelectricity (Methuen, London, 1960).

ZT or Cost?

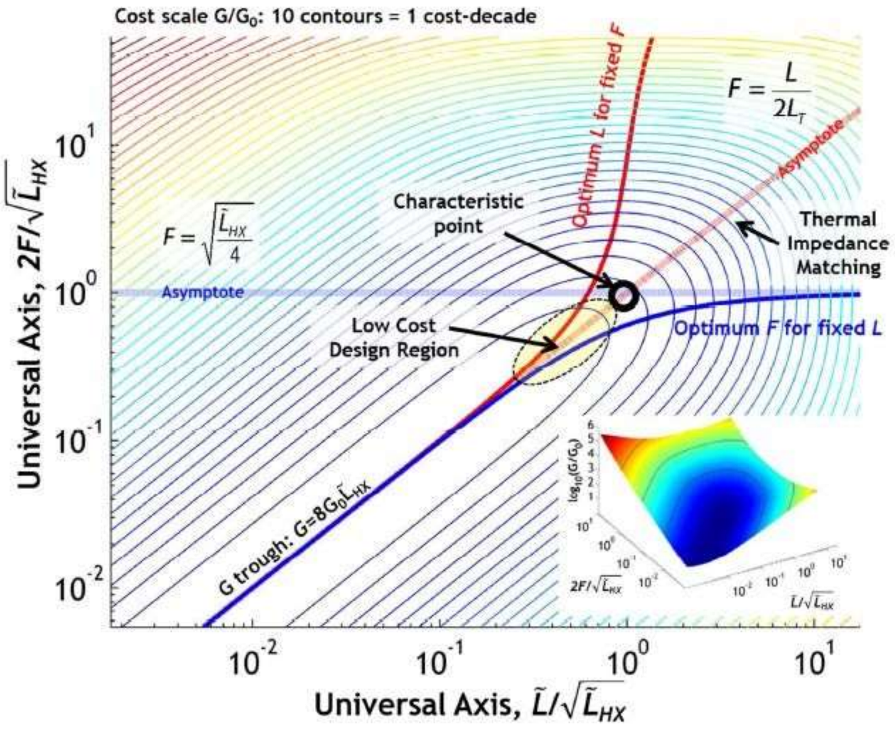
Lowest system cost/W is usually dominated by heat exchanger cost rather than TE material cost

- even \$200/kg (Bi_2Te_3) is OK

Power increases with ZT so cost directly depends on ZT but not TE cost

$$\frac{Cost}{W} \approx \left(\frac{Cost}{Area}\right)_{HX} \cdot \frac{1}{ZT}$$

ZT is TE cost metric



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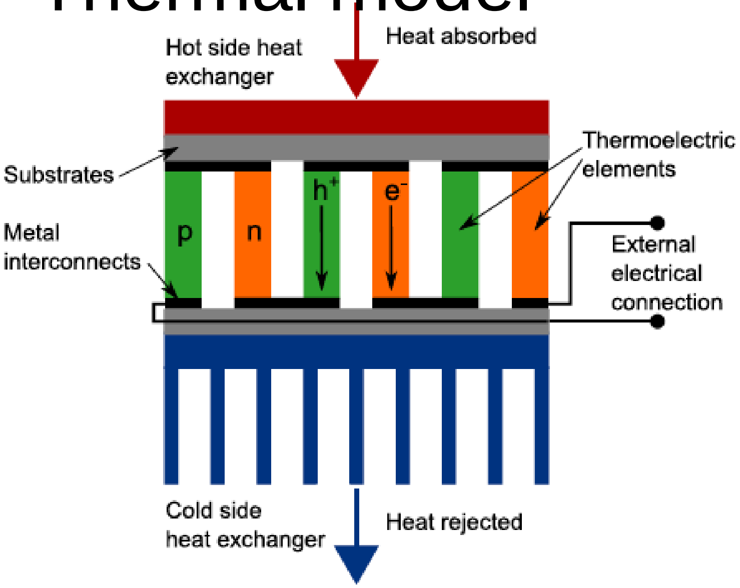
N.R Kristiansen, Snyder, *et al. J. Electronic Materials* 6, 1024 (2012)
Chris Dames, *Scripta Materialia* 111 16–22 (2016)

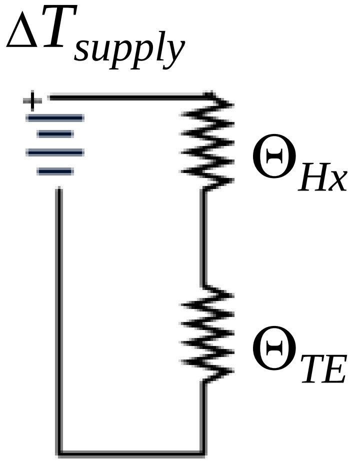
Thermoelectric Conceptual Design Wood Stove

http://www.caframolifestylesolutions.com/ecofan/

Power Estimate

Thermal model





Heat transfer Coefficient

Cross sectional Area A

$$h_{Hx} = 1/\Theta_{Hx} A_{Hx}$$

forced air — forced water

$$h_{Hx} \approx 0.004\,\mathrm{W/cm^2K} \qquad h_{Hx} \approx 0.6\,\mathrm{W/cm^2K}$$

$$\frac{P_{max}}{A_{Hx}} = \frac{\Delta T_{supply}^2 h_{Hx} \eta_{r,d}}{4T_h}$$

thermal impedance match sets target size of TE modules

$$\eta_r \approx 0.15$$

for Bi_2Te_3 modules

Baranowski, Snyder et al, J Applied Phys. 113, 204904, (2013)

TE Modules and Use

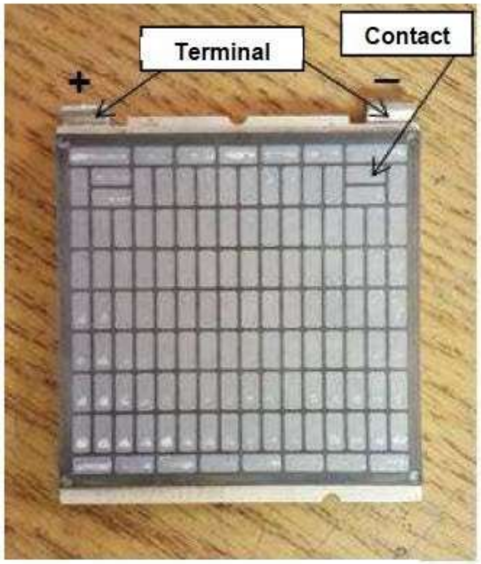


Figure 1: HZ-14 High Voltage

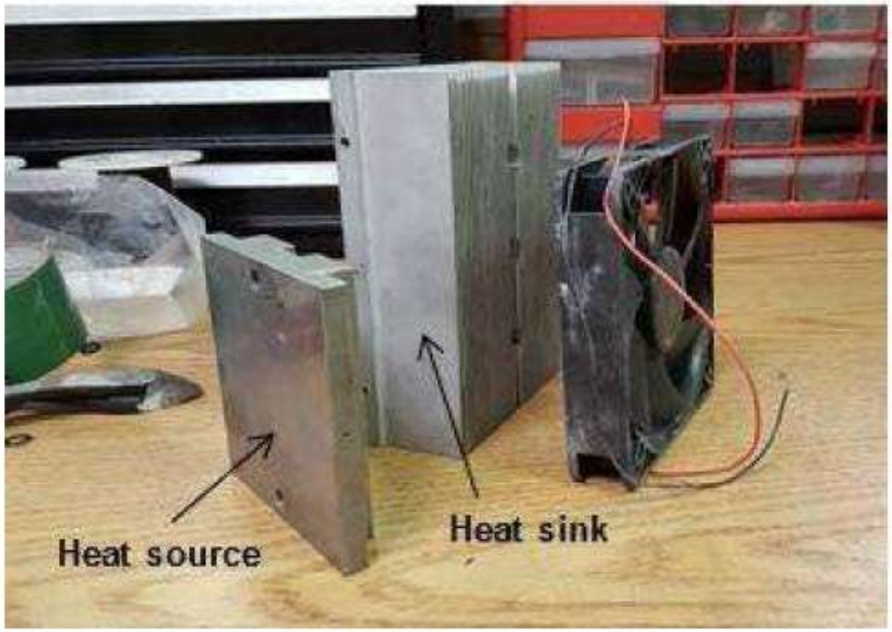


Figure 3: Heat source and sink

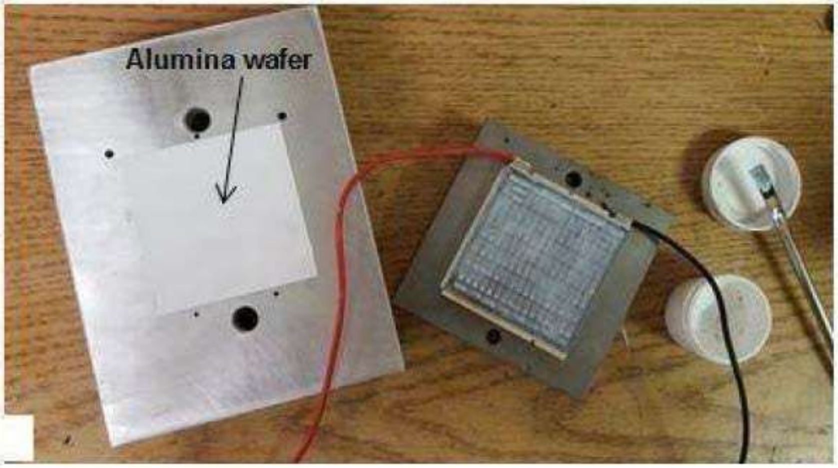
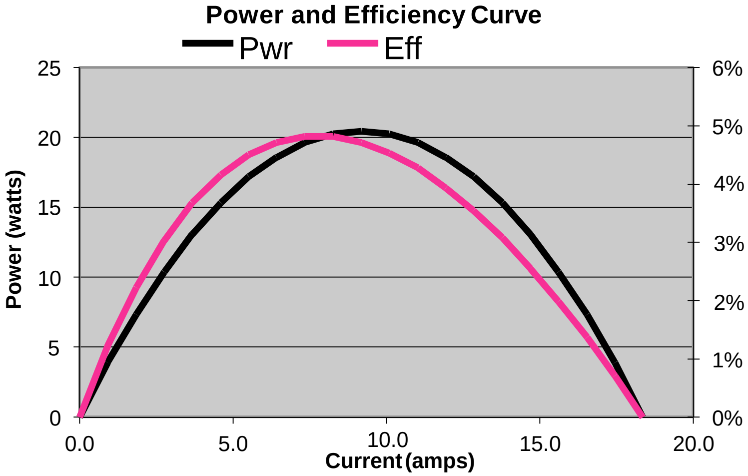


Figure 5: Module insulation



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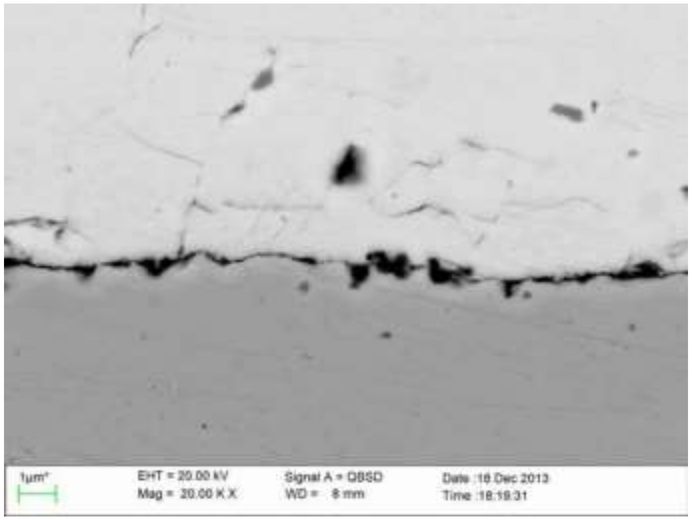
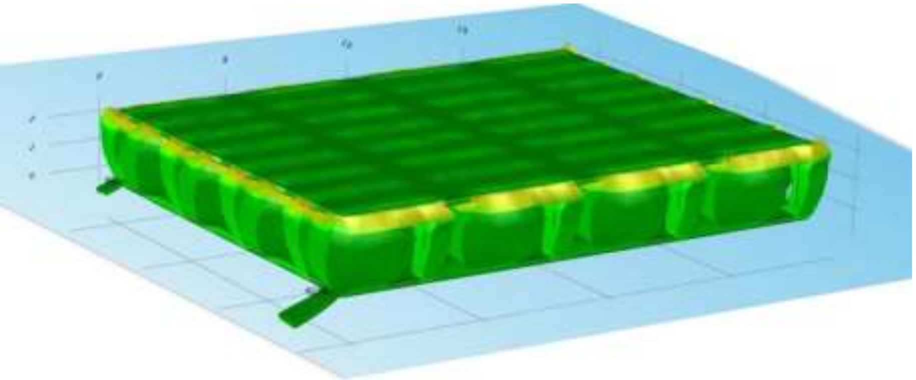
http://hi-z.com/products/

Module Failure Example

Reason for failure: Solder reacted with PbTe at elevated temperatures – crack formation at interface.



Crack at Metal – TE Interface



Stress Model: stress concentration at hot junction

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ITRI Taiwan

Wood Stove Challenges

Performance goal

- 3W commercialized (*Ecofan*)
- 10-20W demonstrated (*Hi-Z*)
- >50 W will be a challenge
- >500 W may require ARPA-E level investment

Modules

- Commercial Bi_2Te_3-based
  - < 250°C special modules (*Hi-Z*)
  - < 120°C for Peltier cooler
- High, Mid temp modules
  - PbTe, H.Heusler, Skutterudite, Silicide, etc.
  - evolving. Blog may be helpful

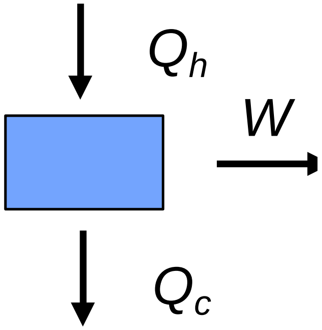
Technical Challenges

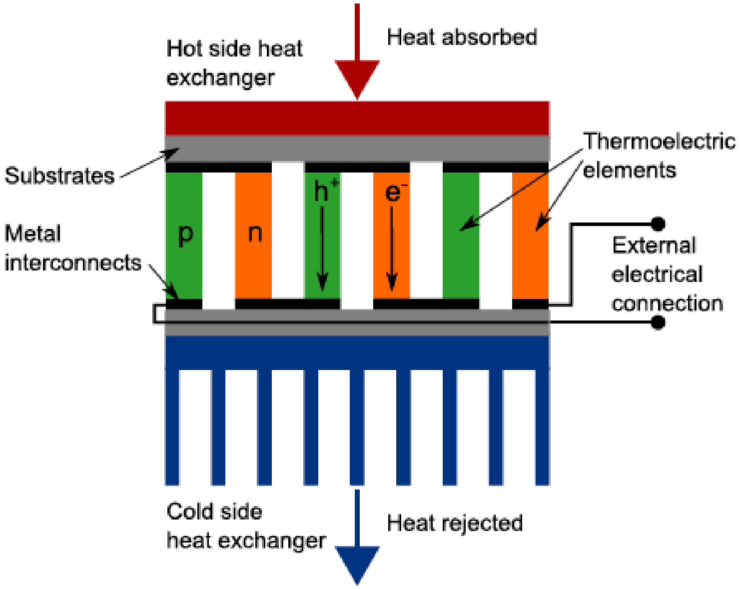
- Hot side Heat Exchanger
  - Thermal Interface to TE module
    - ~200psi pressure and TIM ?
    - **Thermal Interface Resistance**
  - Fouling and Corrosion
- Cold Side Heat Exchanger
  - Passive (no power) or Active (fan)?
  - Interface to TE module
    - **Thermal Interface Resistance**
    - ~200psi pressure and TIM grease
- Thermal management
  - Keep TE at right temperature
    - too small ΔT: no power
    - To high T_{hot}: degrades
- Power Management
  - Impedance match (transformer)
  - Energy storage ?

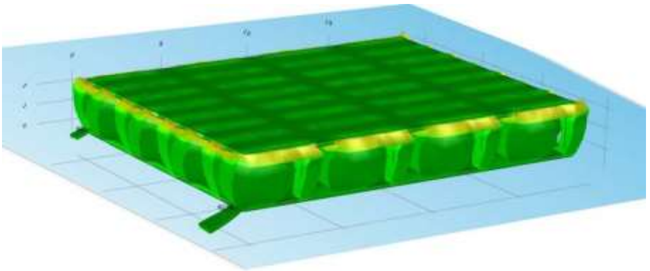
Summary

Design issues

- Thermodynamics
- Heat Exchanger
- Impedance Matching
- Electrical Output
- Mechanical Issues
- Fabrication
- Cost







Acknowledgements

Thermoelectrics
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http://thermoelectrics.matsci.northwestern.edu