THERMOELECTRIC POWER GENERATION
ARPA-E Small Engines Workshop, May 2014

Scope:

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

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SUMMARY – THERMOELECTRIC GENERATORS

**Highlights**

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

**Concerns**

- Material level efficiency in 6-10% range in WHR applications
- System level efficiency in 1-3% range
- Usage of scarce elements
- Low production volumes
- Slow progress in material improvement
HISTORICAL PERSPECTIVE
THERMOELECTRICS – AN OLD KID ON THE BLOCK

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

192 Watts, at 54 Volts and 3.5 Amps

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

GAS Operated RADIO!

THE INVENTION OF A GENERATION

THE HOME GENERATING STATION
PROVIDES THE FOLLOWING ADVANTAGES

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

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

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

THE CARDIFF GAS LIGHT & COKE CO.

Chief Office and Showrooms
City Showrooms & Ladies’ Best Room
Penarth Showroom
Whitchurch Showroom

BUTE TERRACE
ST. JOHN SQUARE
STANWELI ROAD
CHURCH ROAD

THERMO-ELECTRIC RECEIVER

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

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

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

Water heater or gas furnace pilot light control
750 mV, ~50 mW
30 mV, ~10 mW
TECHNOLOGY BASICS
CONVERSION OF HEAT TO POWER

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

Construction of a typical commercial device

\[ Z = \frac{\sigma S^2}{\kappa} \]
TYPICAL THERMOELECTRIC SEMICONDUCTORS

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

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

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

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

Example:

- $T_h = 500^\circ C$
- $T_c = 100^\circ C$
- $ZT_{avg} = 0.6$

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

$\eta = 7.8\%$
Theoretical Efficiency of a Couple

Assumption: no parasitic losses.

Cars and trucks duty cycle

p-type Skutterudite
PROGRESS IN TE MATERIALS

Painfully slow, compared to other solid state technologies

Academic publications, not reduced to practice
CHALLENGES:
Thermal
Electrical
Mechanical
Chemical

- Oxidation and sublimation
- CTE mismatch of layers
- High thermal gradients
- Parasitic electric losses
- Parasitic thermal losses
- Brittleness of TE materials
APPLICATIONS AND ECONOMICS
DOE-SPONSORED WORK SINCE 2005

- 10,000 km on the road
- Up to 600 W at 130 kph
REAL-LIFE DRIVING: BMW X6 AND LINCOLN MKT
DEVICES – TOWARDS VOLUME MARKETS

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

Non-condensing residential boiler

10-300 W to power:
- Controls?
- Communications?
- Pumps?
- Blowers?
ECONOMICS – THE CURSE OF $1/W

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

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

Between $30 and 200/W
Sold in millions

~$60/W
Sold in thousands
VOLUME ECONOMICS

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

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

Economics is explored in the current DOE EERE program
MASS CULTURE VIEW OF WASTE HEAT RECOVERY
### SUMMARY – THERMOELECTRIC GENERATORS

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#### Concerns
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