Energy Harvesting (EH) – Energy Needed / Energy Available

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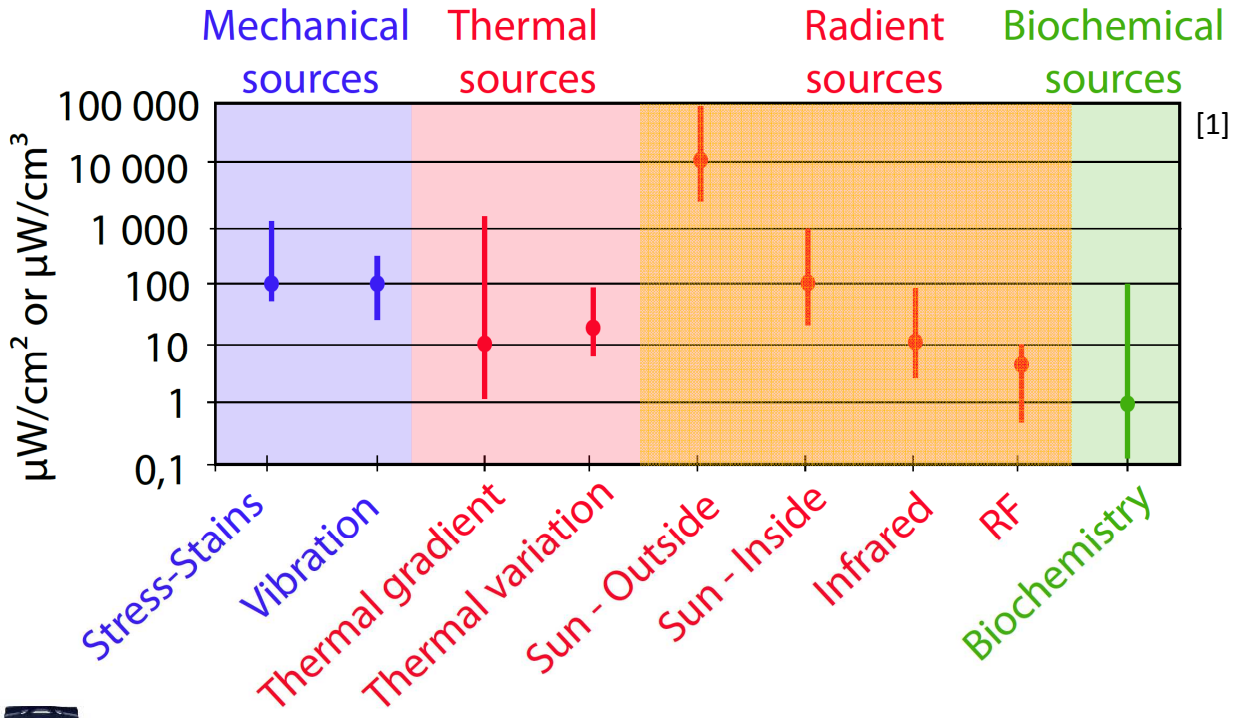
Energy Available



[1]

(10 mW) (1 mW) (100 µW) (10 µW) (1 µW) (100 nW) (10 nW)

***η* (efficiency) matters for EH!**

[1] Somov and Giaffreda (2015) Powering IoT Devices: Technologies and Opportunities.

Energy Harvesting (EH)

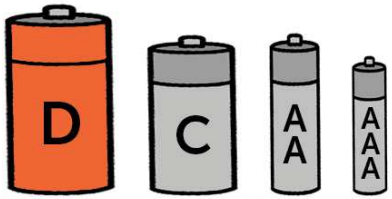
Wikipedia "definition": Energy harvesting is **the process by which energy is derived from external sources**, **captured, and stored** for small, wireless autonomous devices [2].

ISA definition [3]:

- No wires.
- No batteries.
- No maintenance.

ISA standards for wireless sensor nodes based on three cases using the license free 2.4 GHz radio IEEE 802.15.4 standard:

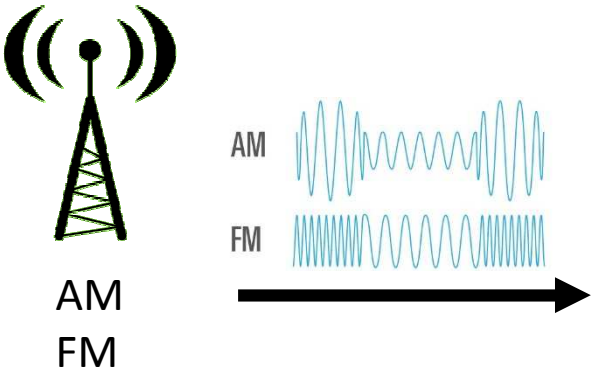
Case 1: 2500 μW = "D" cell for 4 months.
Case 2: 1000 μW = "C" cell for 3 years.
Case 3: 300 μW = "AA" cell for 3 years.

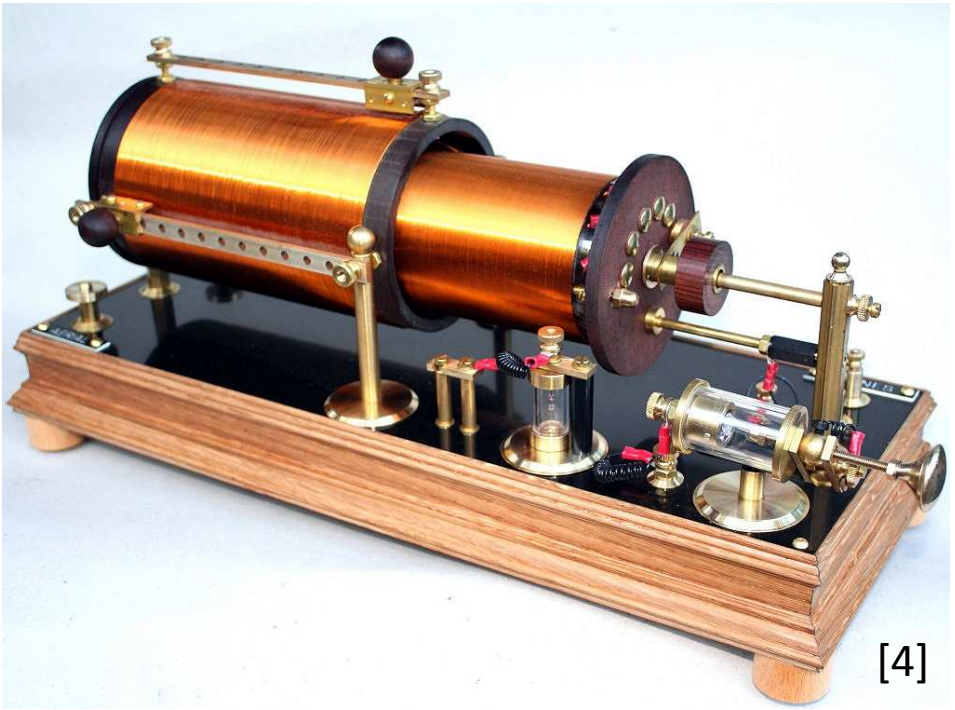


Small scale distributed energy generation.

[2] www.wikipedia.org/wiki/Energy_harvesting. [3] ISA InTech Magazine (2011) Special Section: Energy harvesting.

Example 1: “Crystal Radio” – Nearly Los Art

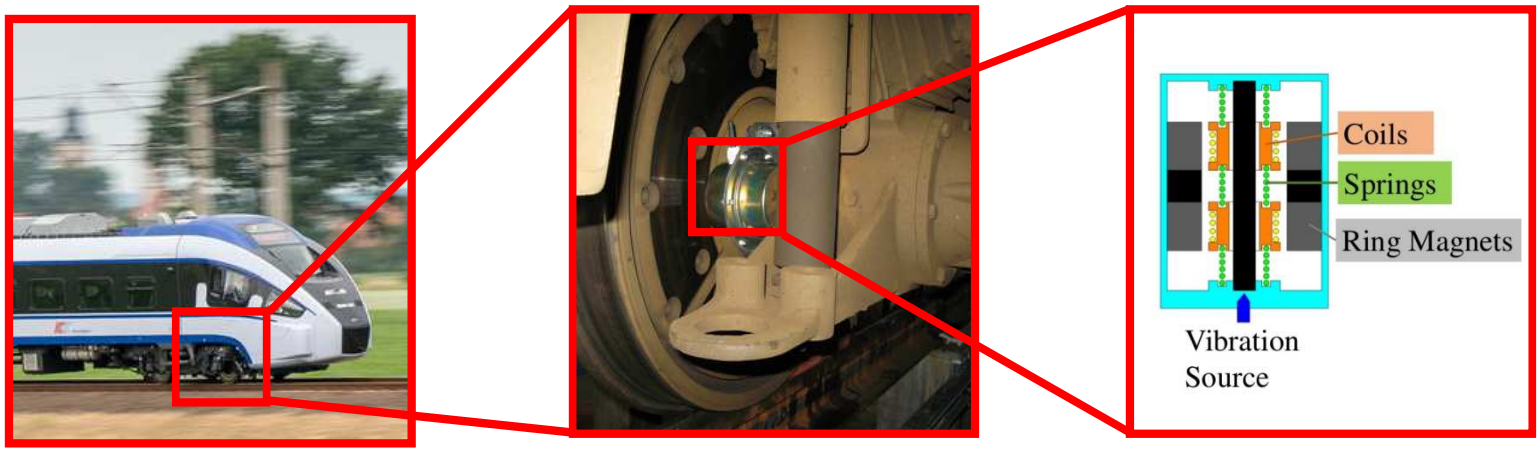



[4]

- Wireless power transmission using RF signals.
- Radio only needs 50 *pW* **without** an external power source.
- Over hundreds of km range.
- **Works since 1894!**

[4] www.crystalreceiver.co.uk/loosecoupler.html

Example 2: Vibration EH from Trains



Train vibrations:

- Wheels.
- Axle bearings.
- Gearboxes.
- Traction motors.
- Tracks.

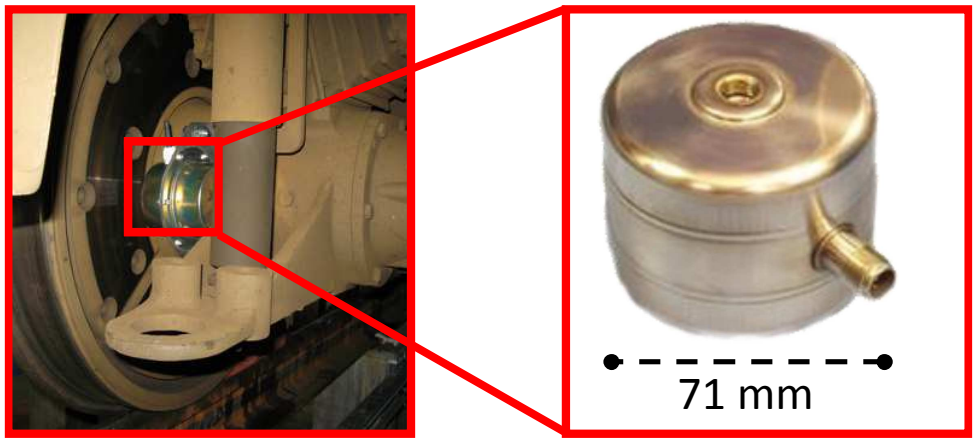
[5]

[5] www.perpetuum.com

Example 2: Vibration EH from Trains

Continuous wireless **machine health monitoring under harsh environmental conditions** with a Mean –Time –To – Failure of 440 years and data on:

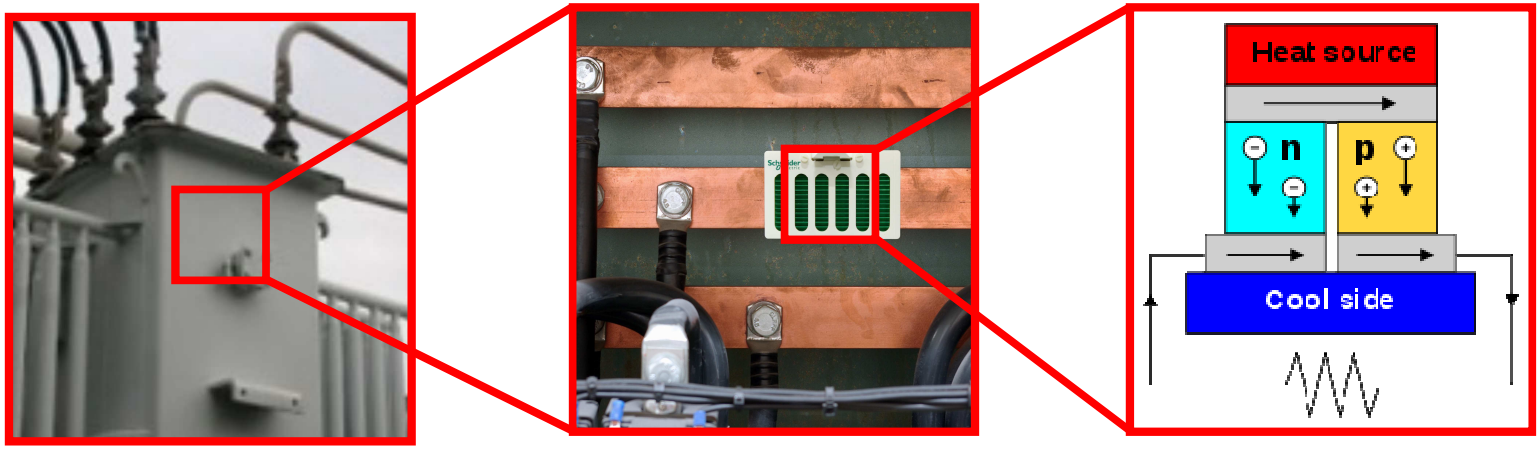
- Bearing failure analyses of correct wheel and correct fault.
- Track conditions.
- 1.8 million sets data/day e.g.: vibration, temperature and oil analysis.
- Wireless data transmission.



[5]

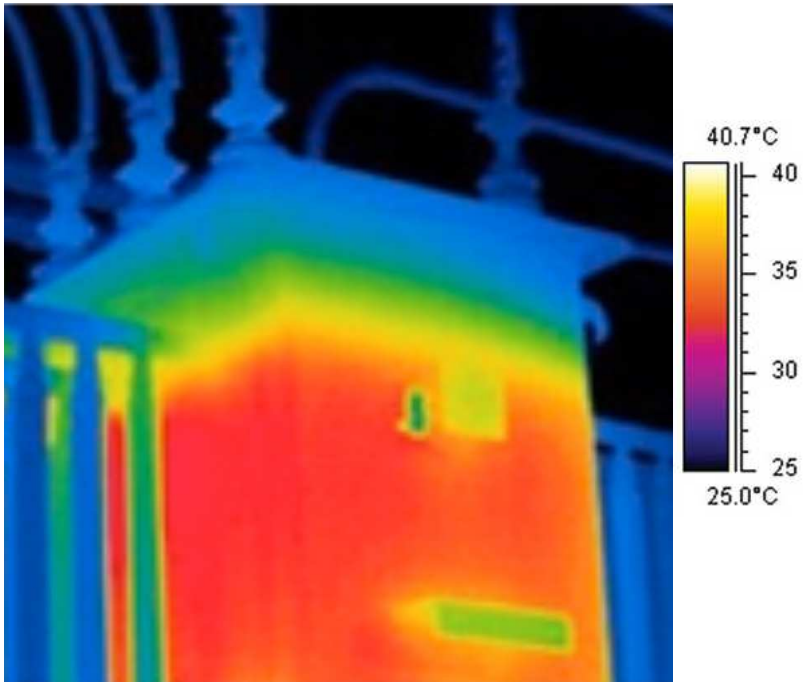
[5] www.perpetuum.com

Example 3: Thermal EH in Power Transformers



Heat in low voltage power distribution:

- High current bus ways.
- Unbalanced loads.
- Ambient heat sink.

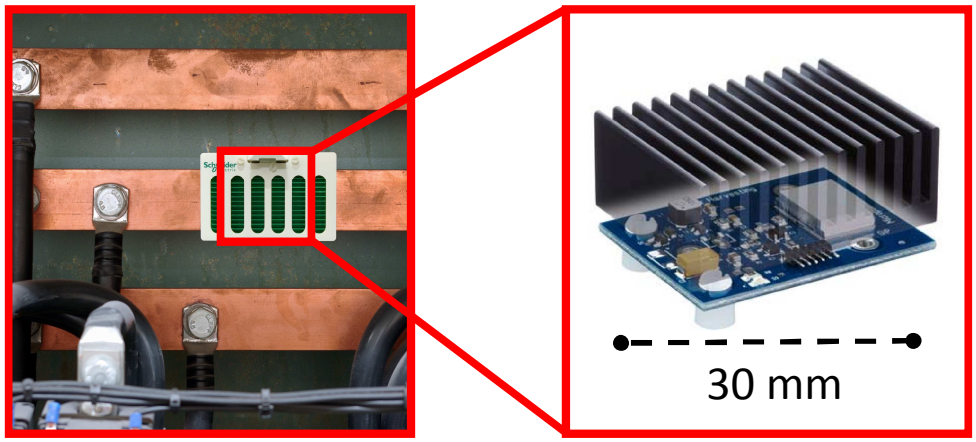


[6] www.micropelt.com

Example 3: Thermal EH in Power Transformers

Continuous wireless **machine health monitoring in central location** and data on:

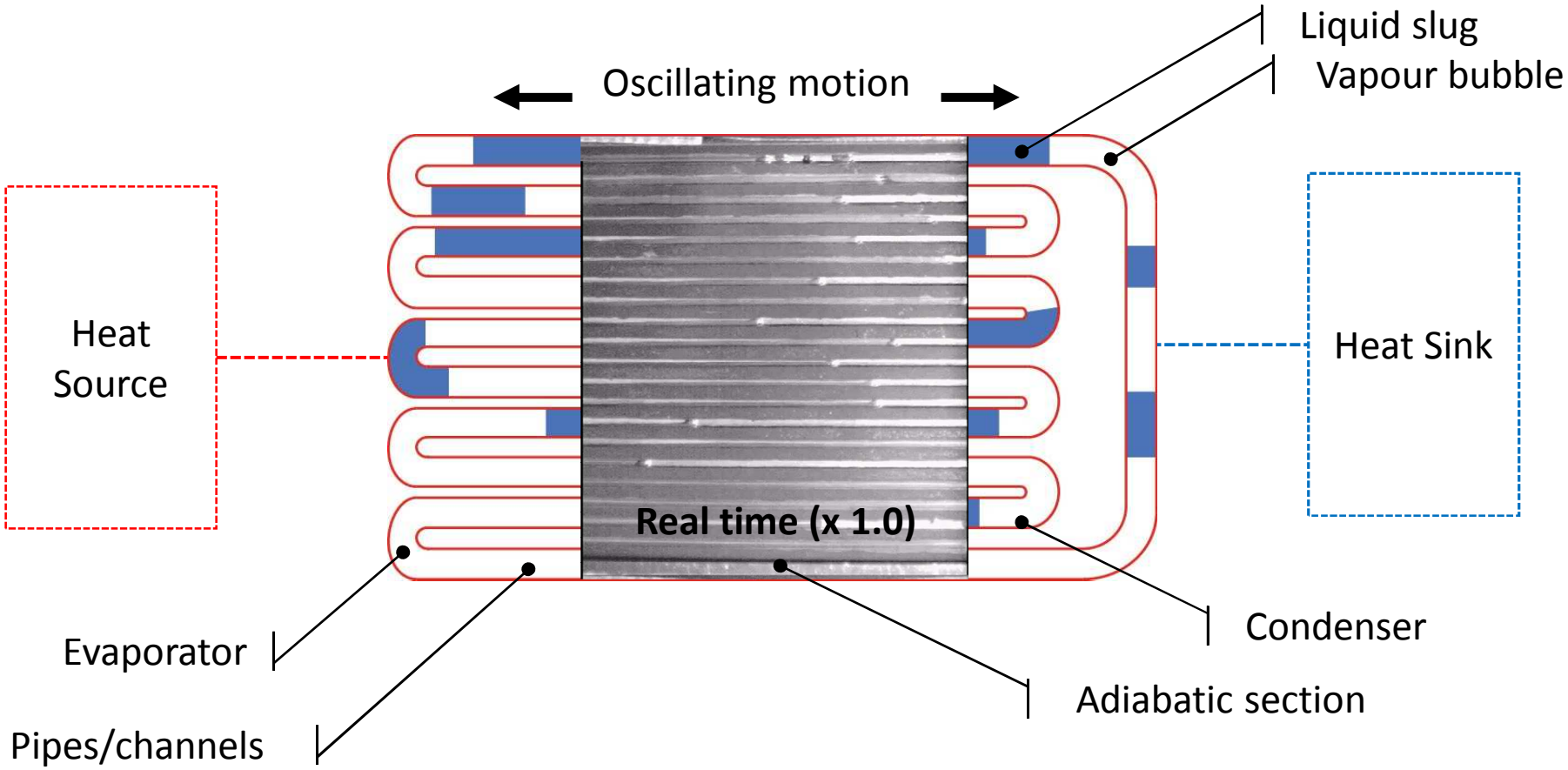
- Temperature and voltage at the bus.
- Low oil level in transformer.
- Loose or corroded joints.
- Ground conductor carrying current.
- Insulation failure.
- Mechanical binding/friction.



[6]

[6] www.micropelt.com

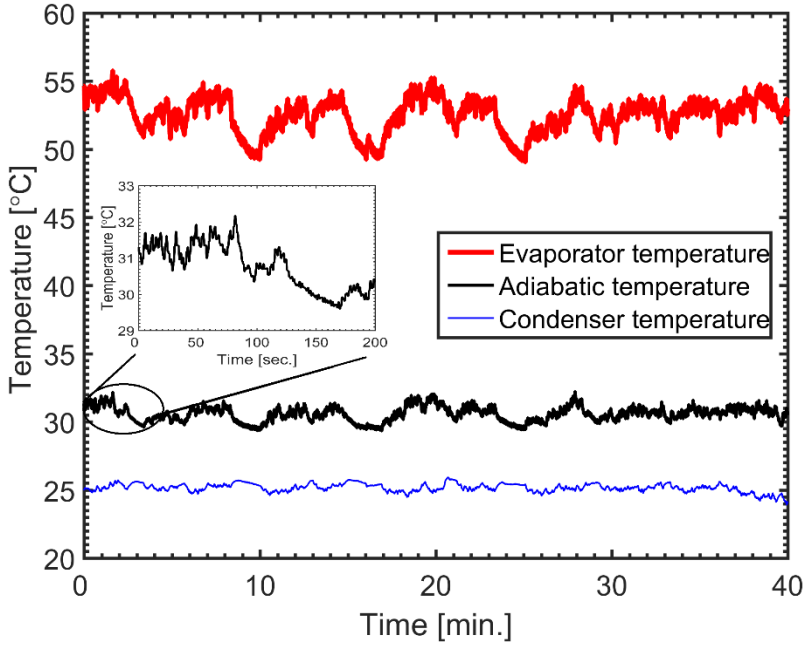
Oscillating Heat Pipes I



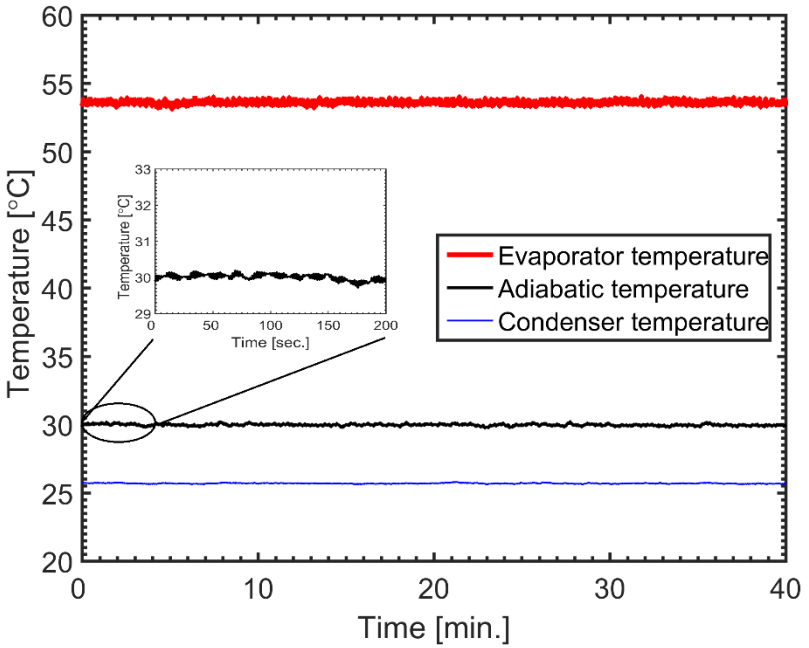
Two phase instability of the working fluid creates a powerful heat exchanger.

Oscillating Heat Pipes II

Chaotic mode with **random** temperature oscillation



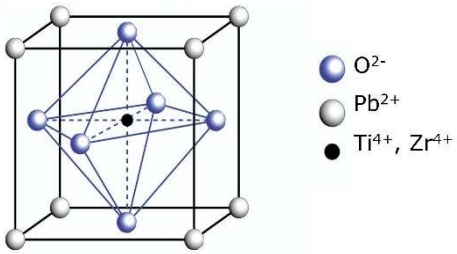
Steady state mode with **symmetric** temperature oscillation



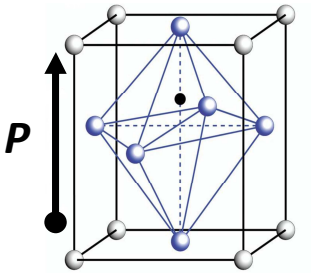
Under **constant thermal boundary condition** the OHP exhibits **rapid-** and **high-temperature oscillations (but we know very little about it).**

[8] Zabek et *al*. (2016) A novel pyroelectric generator … for waste heat recovery and thermal energy harvesting.

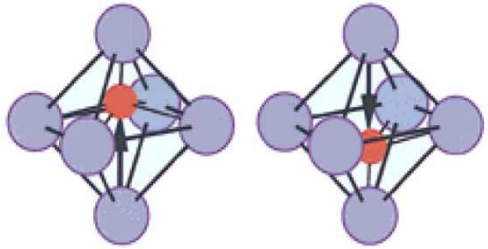
Ferroelectrics Materials I



$T > T_c$



$T < T_c$



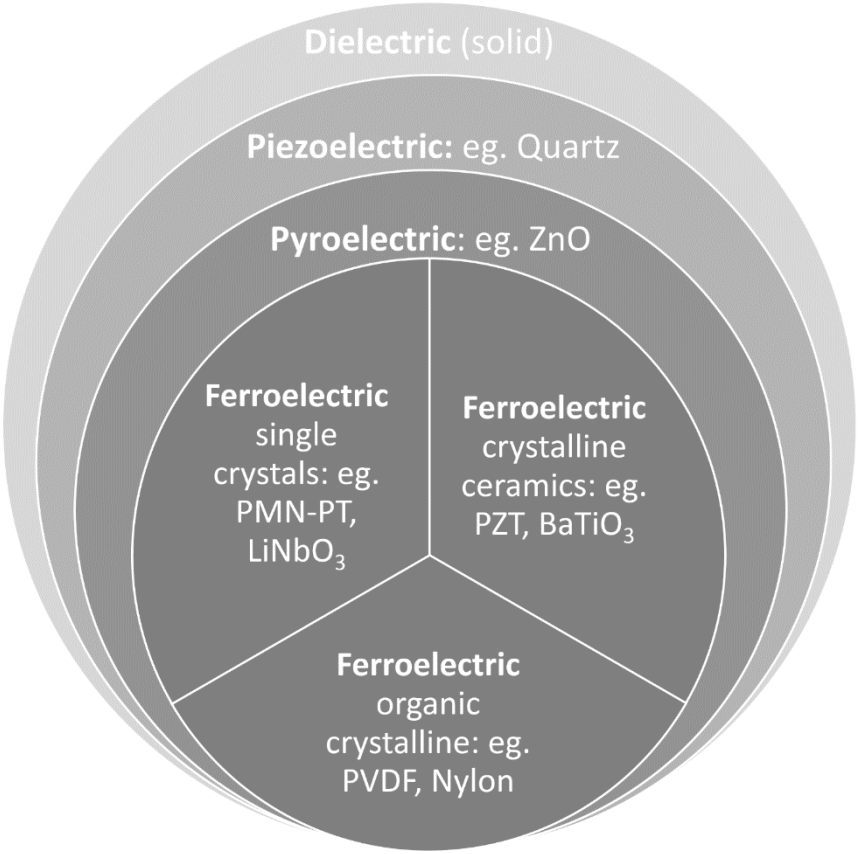
Polarisation: UP DOWN

Ferroelectric dipole moment is subjected to:

- Electric fields (ferroelectric hysteresis).
- Mechanical force (piezoelectric effect).
- Temperature (pyroelectric effect).

“Functional” material.

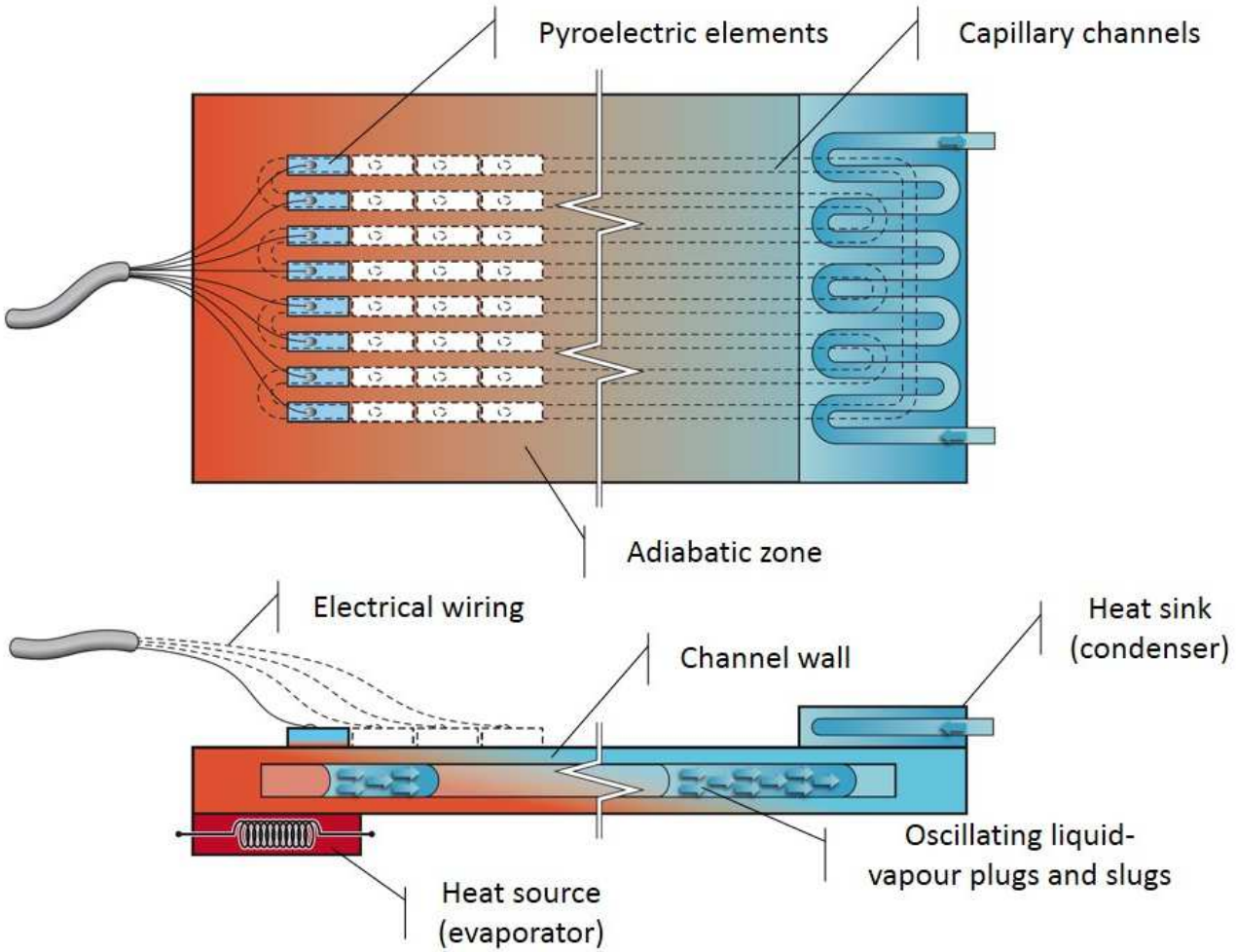
Ferroelectrics Materials III



Potentially over 1000 undiscovered materials exhibiting ferroelectric behaviour.

[8] Zabek (2016) Pyroelectric Structures and Device for Thermal Energy Harvesting.

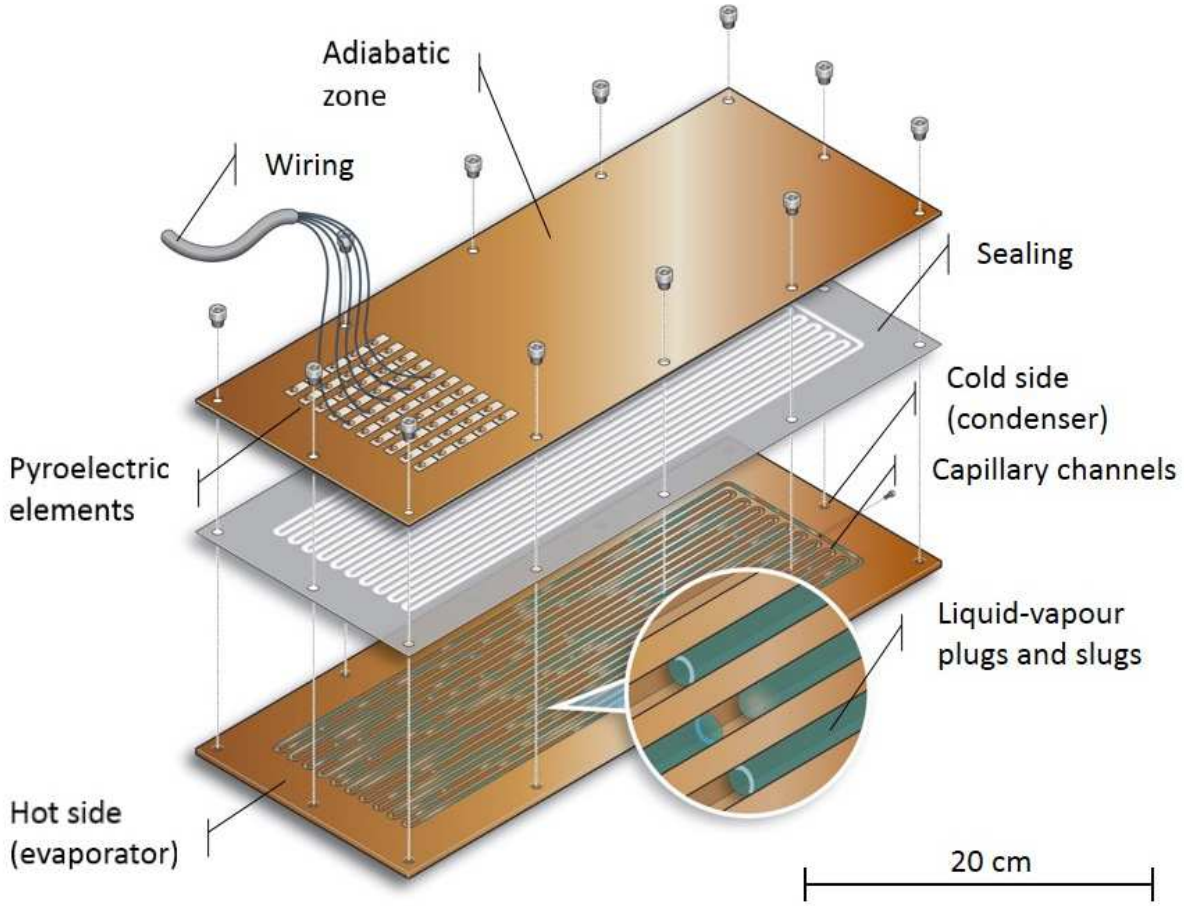
Pyroelectric Oscillating Heat Pipes I



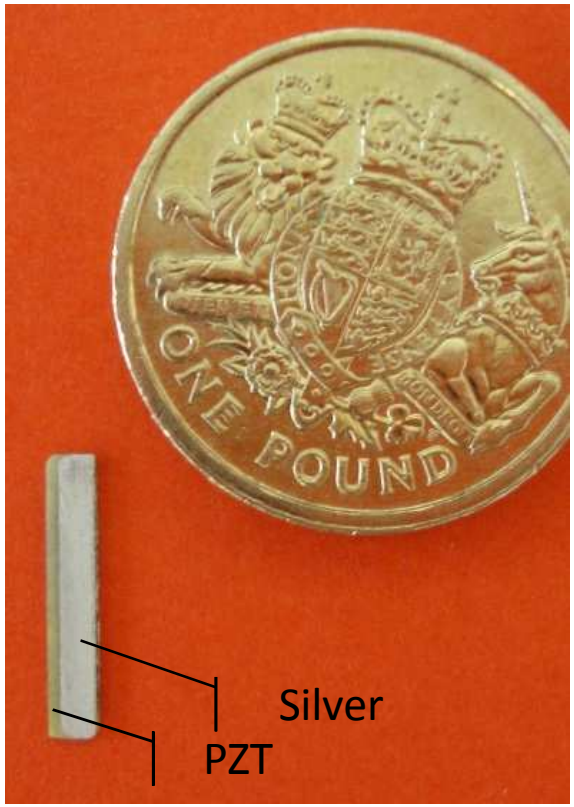
Change in thermo-fluid properties between **liquid** and **vapour phase.**

[8] Zabek et *al*. (2016) A novel pyroelectric generator … for waste heat recovery and thermal energy harvesting.

Pyroelectric Oscillating Heat Pipes II



Pyroelectric element:

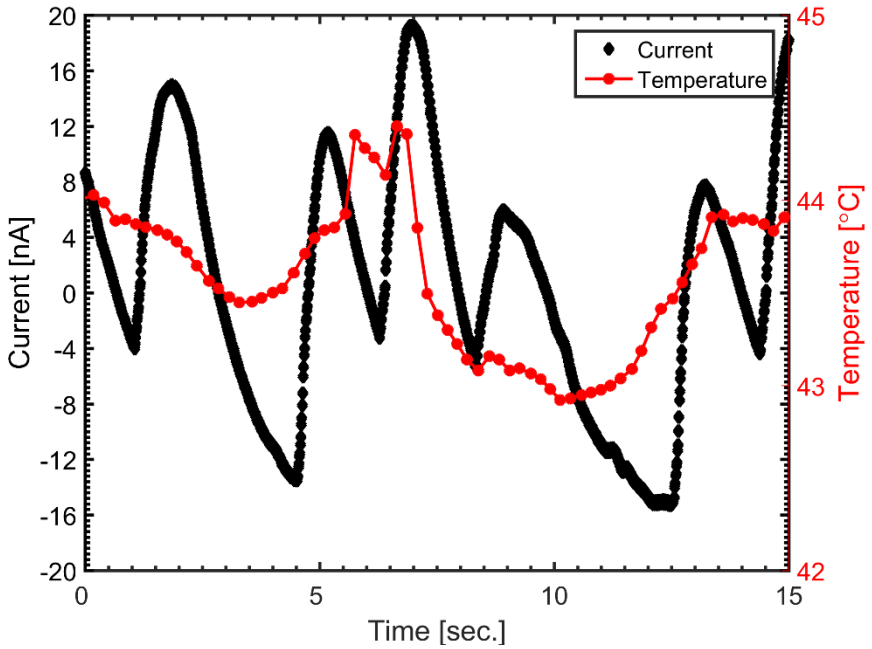


Proof of **concept.**

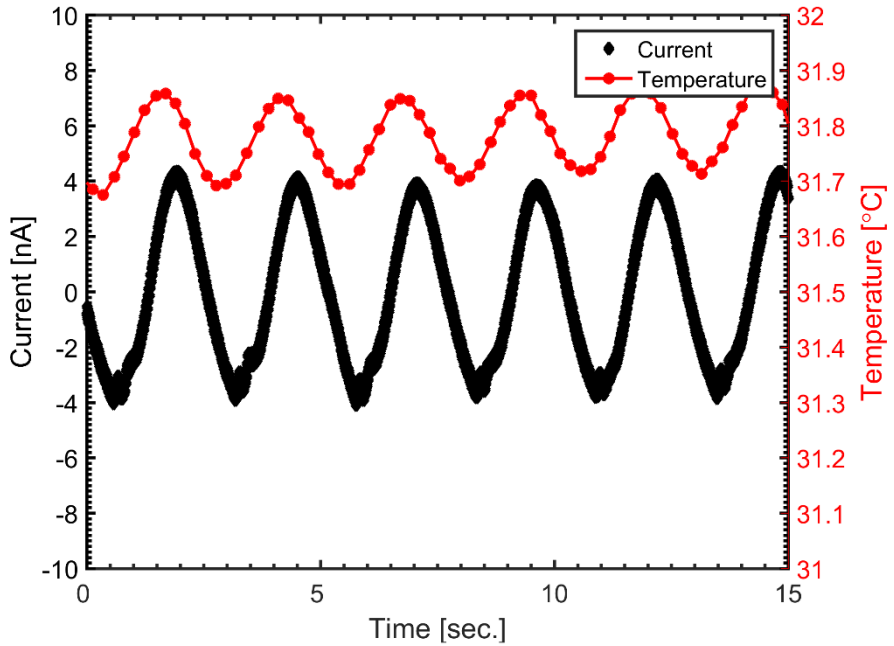
[8] Zabek et *al*. (2016) A novel pyroelectric generator … for waste heat recovery and thermal energy harvesting.

Pyroelectric Oscillating Heat Pipes III

PMN-PT current chaotic



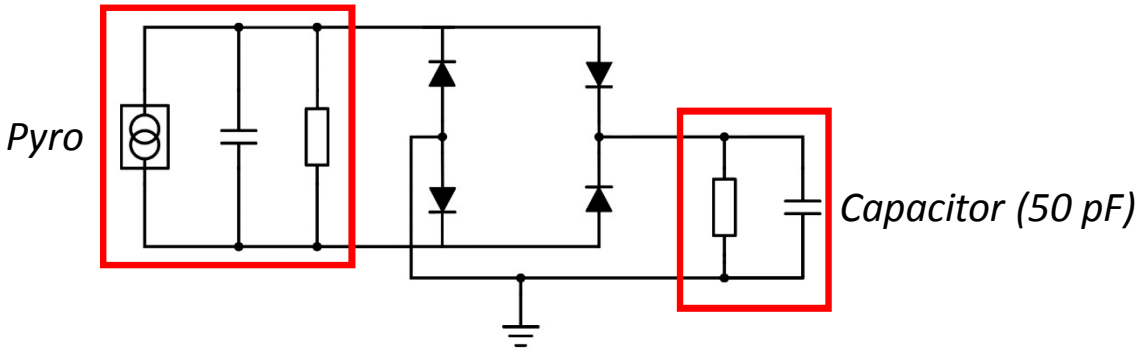
PMN-PT current symmetric



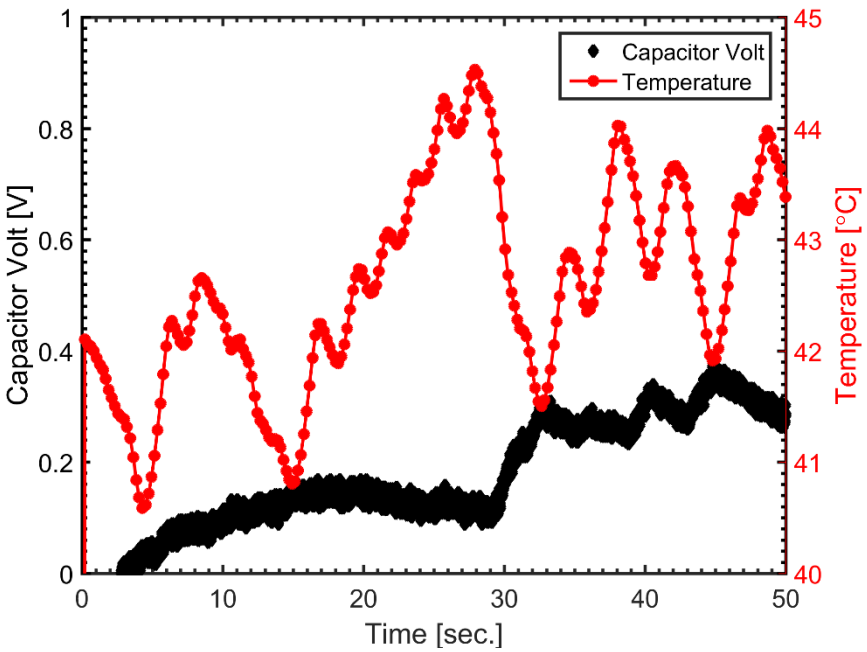
- **Large** changes in temperature.
- **Fast** changes in temperature.
- **High** pyroelectric current.

[8] Zabek et *al*. (2016) A novel pyroelectric generator … for waste heat recovery and thermal energy harvesting.

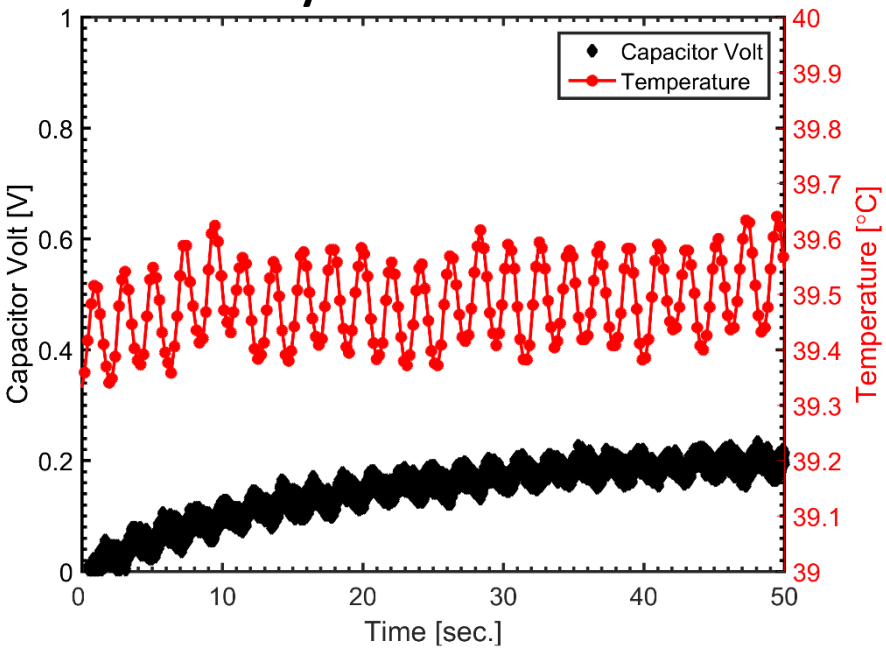
Pyroelectric Oscillating Heat Pipes IV



Rectified **chaotic** current



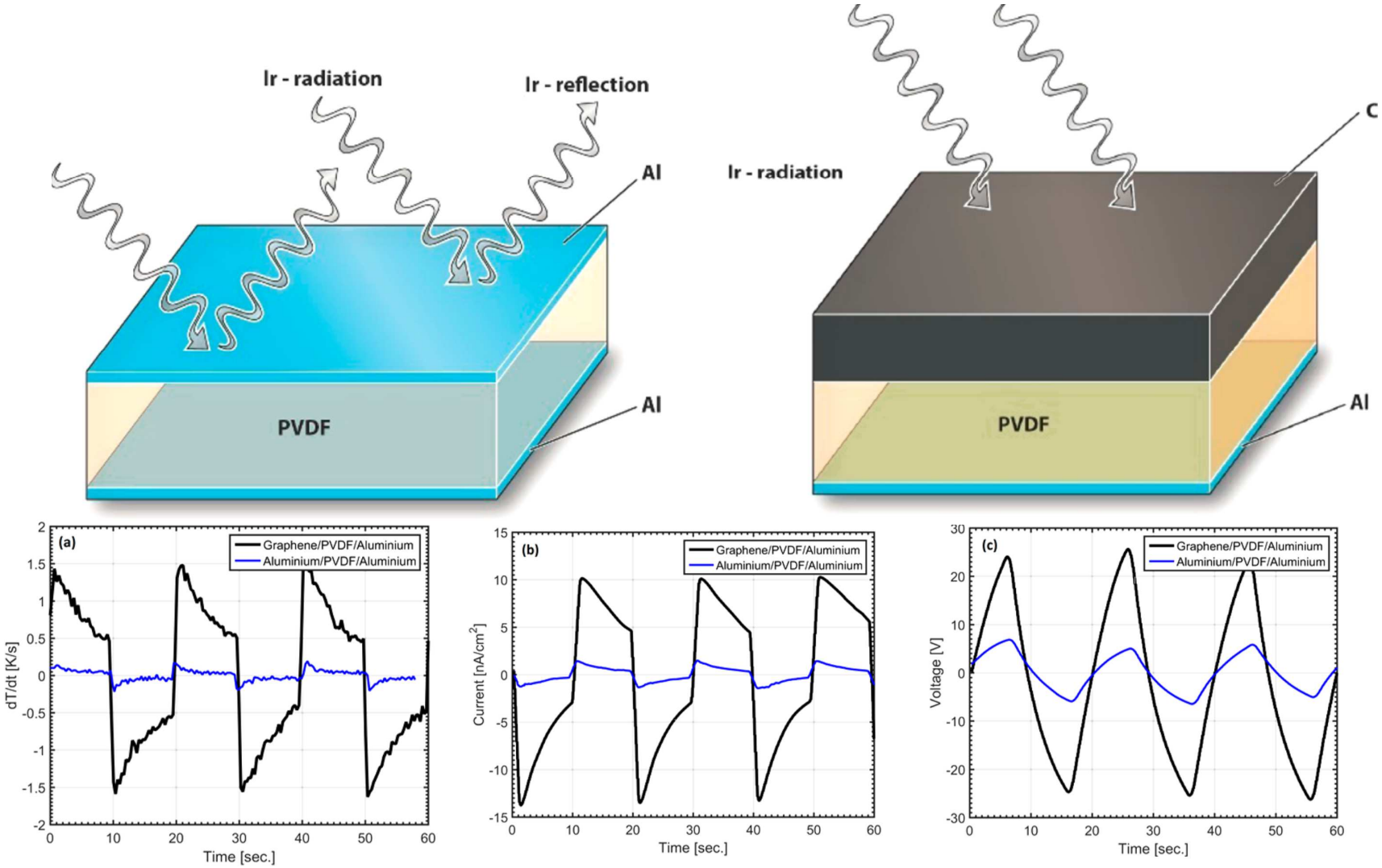
Rectified **symmetric** current



More energy recovered in chaotic operation than in symmetric operation.

[8] Zabek et *al*. (2016) A novel pyroelectric generator … for waste heat recovery and thermal energy harvesting.

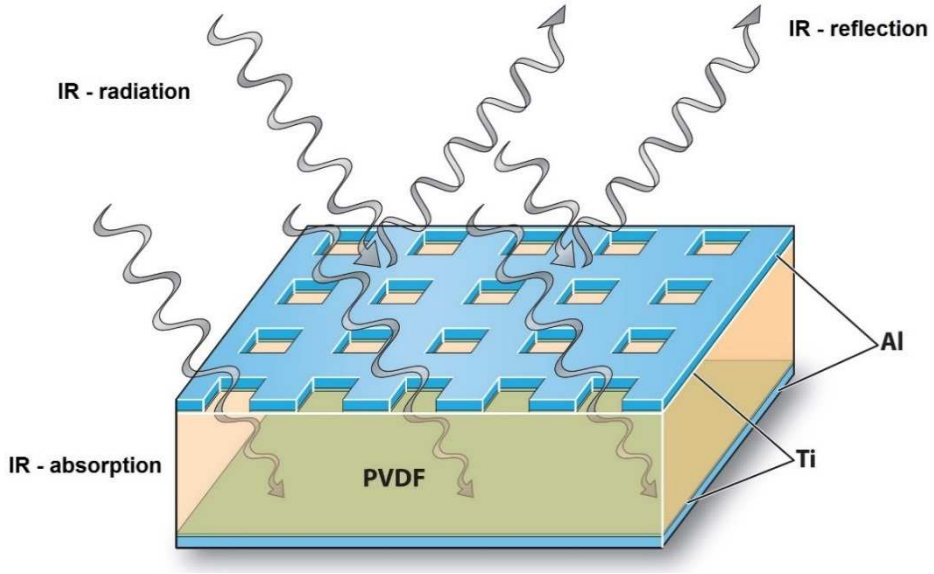
Heat Transfer Enhancement for Pyroelectric EH

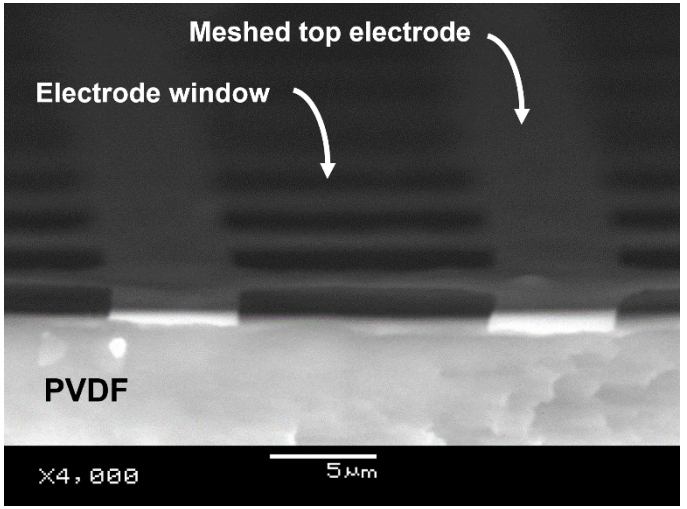


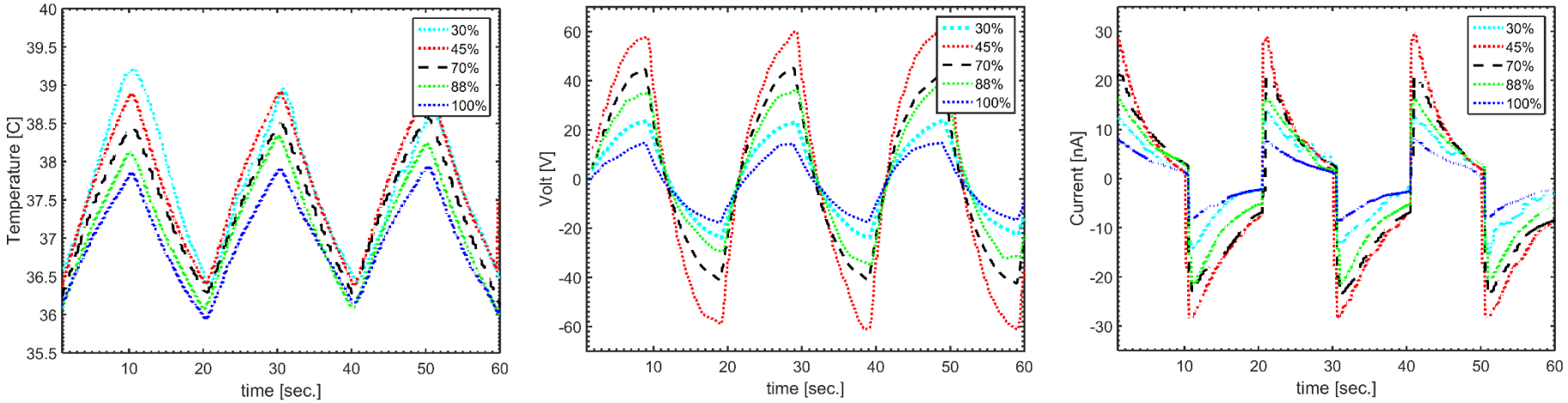
Graphene ink electrodes improve pyroelectric current and voltage by 4.3 times.

[10] Zabek et *al*. (2017) Graphene Ink Laminate Structures on PVDF for Pyroelectric Thermal Energy Harvesting and Waste Heat Recovery.

Meshed Electrodes for Pyroelectric EH







Meshed electrodes improve pyroelectric current and voltage by 6 times.

[11] Zabek et *al*. (2015) Micropatterning of flexible and free standing PVDF films for enhanced pyroelectric energy transformation.

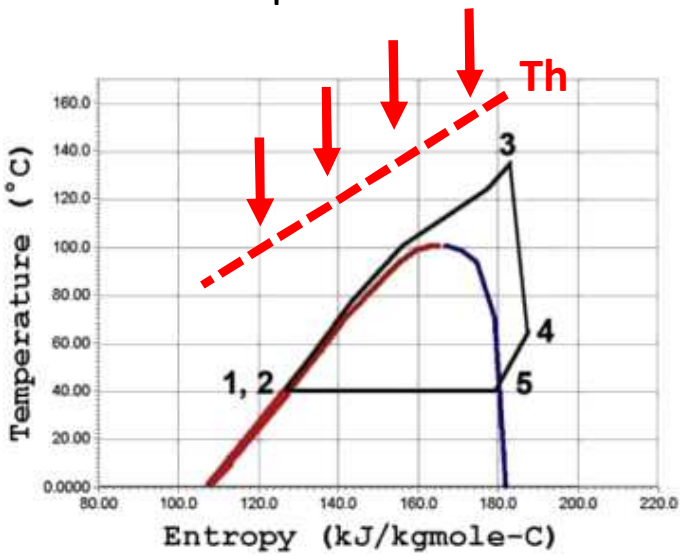
Organic Rankine Cycle – Crude Oil Development

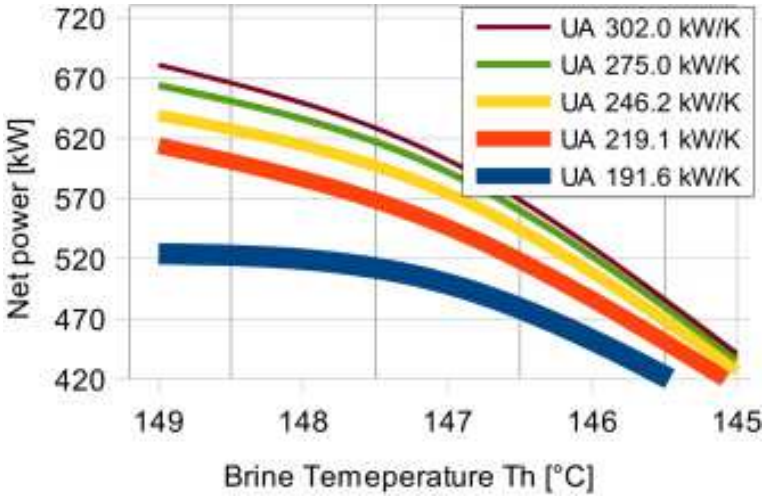
Overall heat transfer coefficient U and area A in a heat exchanger with set boundaries T_{LM}.

T_{LM} = in waste heat recovery is usually constant.

$$UA = \frac{Q}{T_{LM}}$$

Brine Temperature decrease





[12] Zabek et *al*. (2013) Optimization of waste heat utilization in oil field development employing a transcritical ORC for electricity generation.

Conclusions

- Temperature level is not necessarily a variable in EH and waste heat recovery.
- Various external and free energy source exits.
- **Commercially viable Energy Harvesting (EH) applications are out there.**
- Finding applications with strong benefits from wireless without batteries.
- The inconvenient truth: small scale and low temperature power conversion is not efficient.