NPL National Physical Laboratory

Variability on the performance characterisation of thermoelectric modules

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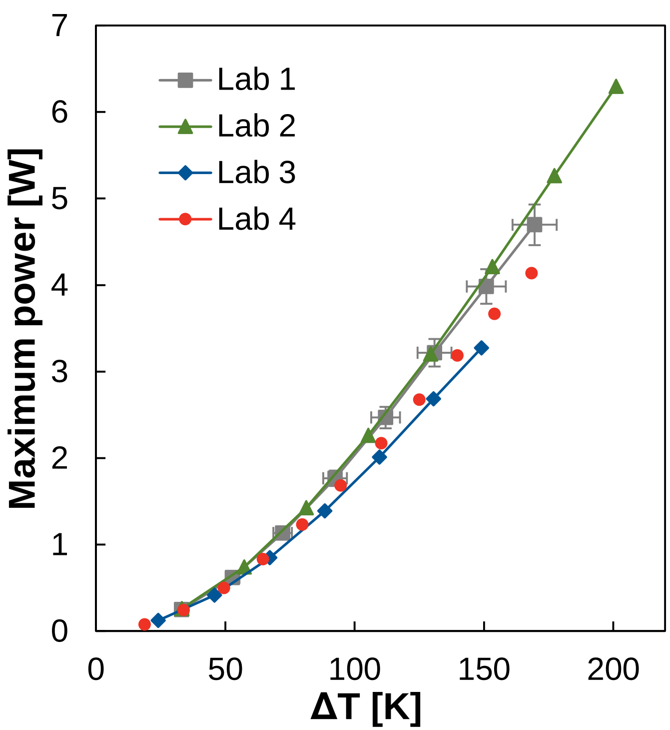
Performance characterisation of TE modules:

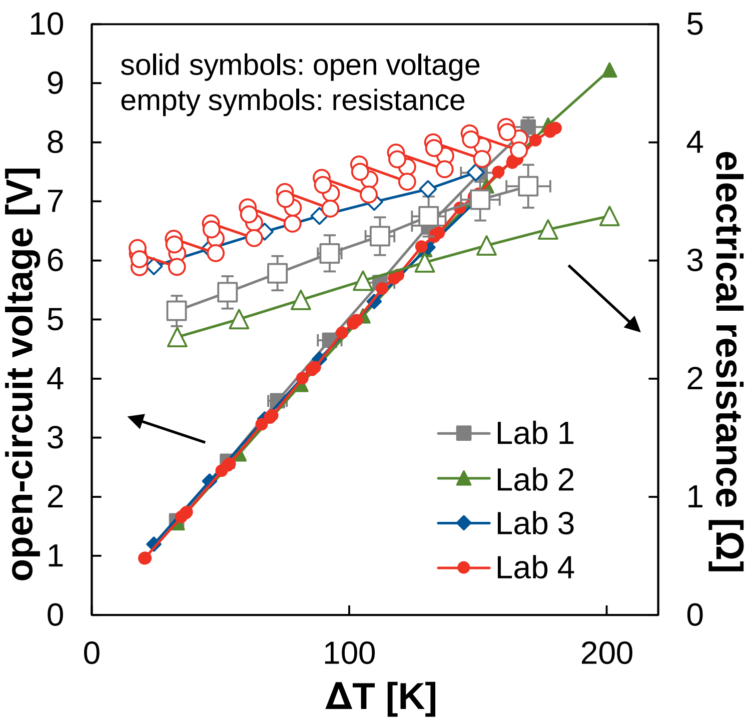
- Apply ΔT
- Measure output voltage (V) and current (I).

Round robin comparison:

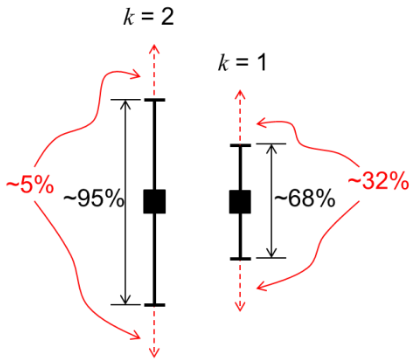
Pmax ~ 25 %

Rint ~ 25%





Measurement uncertainty evaluation



Some facts about uncertainties:

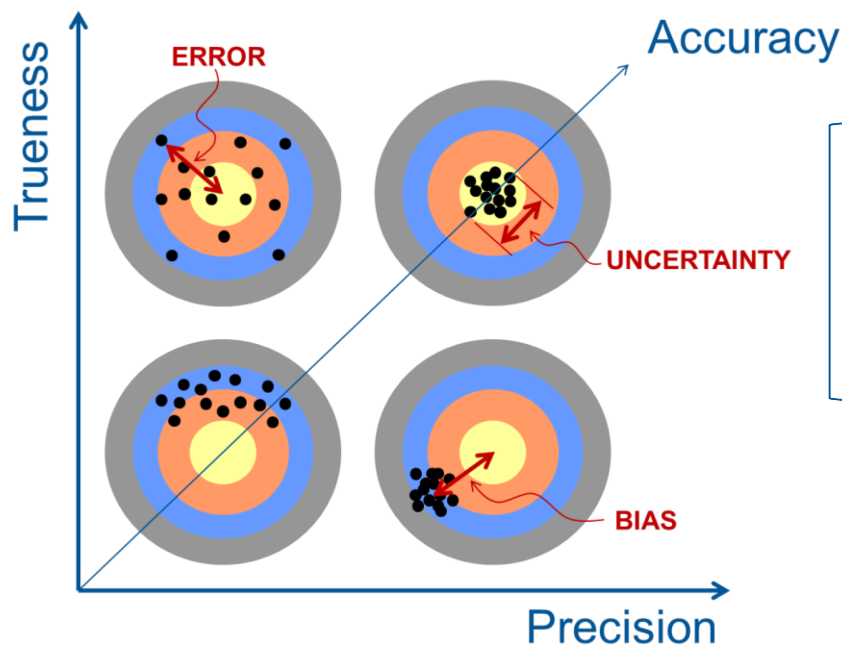
- **Every measurement** is subject to some **uncertainty**.
- A measurement result is **incomplete** without a statement of the uncertainty.
- **Evaluating uncertainty** is important, in particular, when:
  - Maintain quality control during production processes
  - Show compliance with regulations
  - Calibrate instruments
  - Support research and development
  - Demonstrate traceability to national measurement standards
  - Develop, maintain and compare national and international measurement standards
- **Understanding** measurement **uncertainty** is the first step to reducing it

Uncertainty evaluation

Guide to the Expression of Uncertainty in Measurement (GUM)

http://www.bipm.org/en/publications/guides/gum.html

Important concepts



- Precision: measurement dispersion
- Trueness: true value
- Accuracy: true AND precise

Uncertainty calculation

Guide to the Expression of Uncertainty in Measurement (GUM)

- Identify variables $y = f(x_1, \dots, x_j, \dots, x_N)$
- Reduce errors (apply corrections)
- Quantify $u(x_j)$
  - Type A: Statistical method
  - Type B: Non-statistical methods
- Combine $u(x_j)$ $$u_c(y) = \sqrt{\sum_j c_j^{\,2} \cdot u^2(x_j)} \equiv \sqrt{\sum_j u_j^{\,2}(y)}$$
- Extend u_c to U

$$U = k \cdot u_c(y)$$

Level of confidence

$k = 1$	68.3 %
$k = 2$	95.4 %
$k = 3$	99.7 %
$k = 4$	99.99 %
$k = 5$	99.9999 %

Uncertainty calculation

Sources of uncertainty for TEGs

$$y = f(x_1, \ldots, x_j, \ldots, x_N)$$

Thermal contact resistance

- Engineering:
  - **Clamping pressure**
  - **Interface material**
  - Environment (vacuum, air)

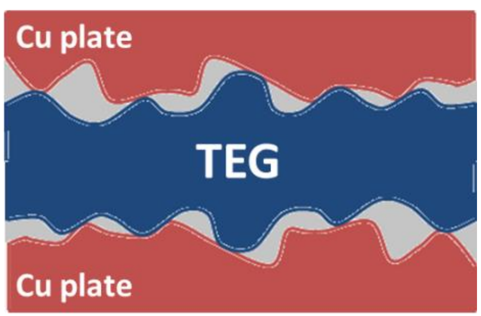
TE materials properties

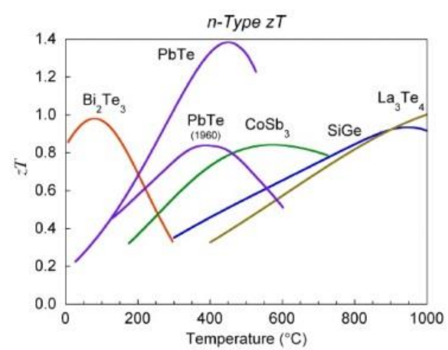
- Physical phenomena
  - **Mean T and ΔT**
  - T stabilisation
  - Meas. method

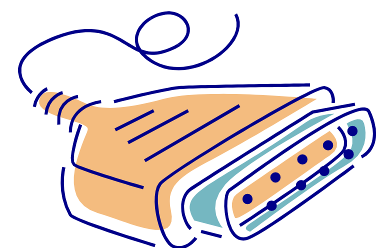
(const Heat Flux Vs. const T)

Data Acquisition

- Instrumental
  - Thermocouples
  - Electronic load
  - Multimeters



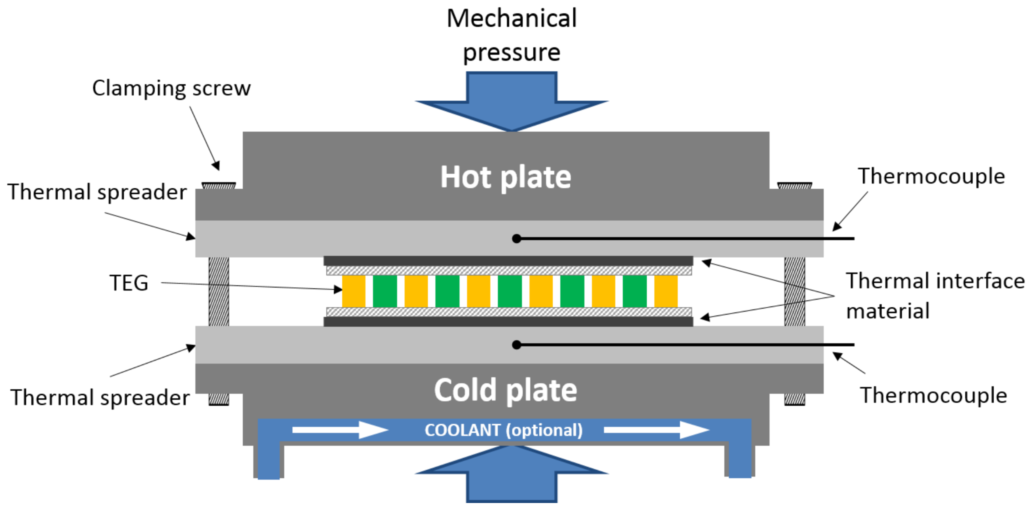


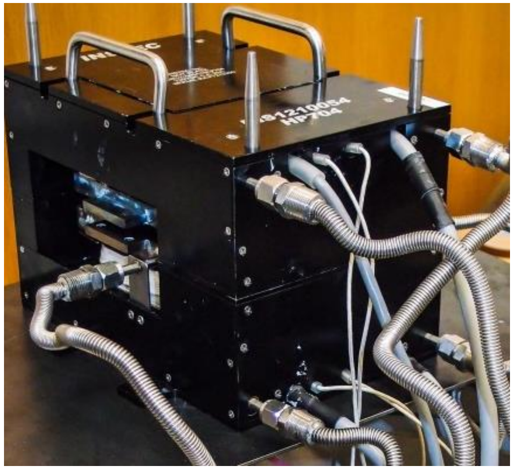


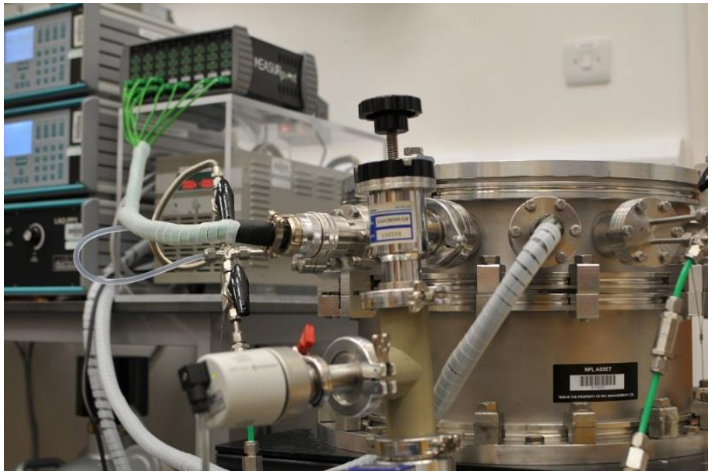
The main sources of uncertainty are those related to **contact resistance** and **materials properties**.

G. Jeffrey Snyder and Eric S. Toberer "Complex Thermoelectric Materials" Nature Materials 7, 105-114 (2008).

Measurement service







- Hot: RT to 700 ^oC
- Cold: - 180 ^oC to 400 ^oC
- Vacuum/Inert atmosphere
- Measurement service available

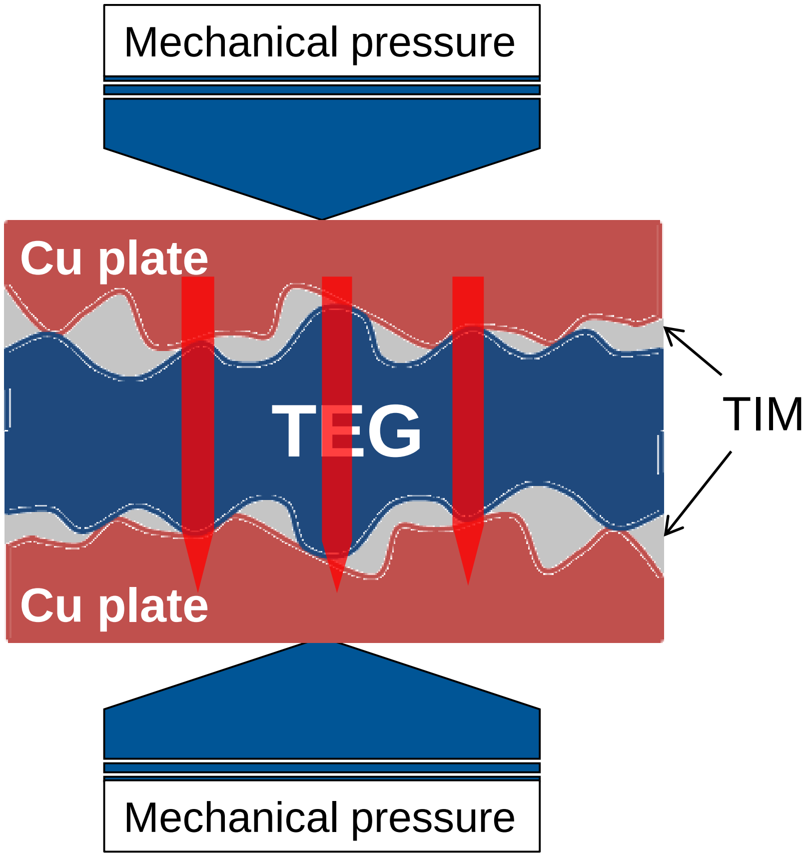
Thermal contact resistance

Main strategies:

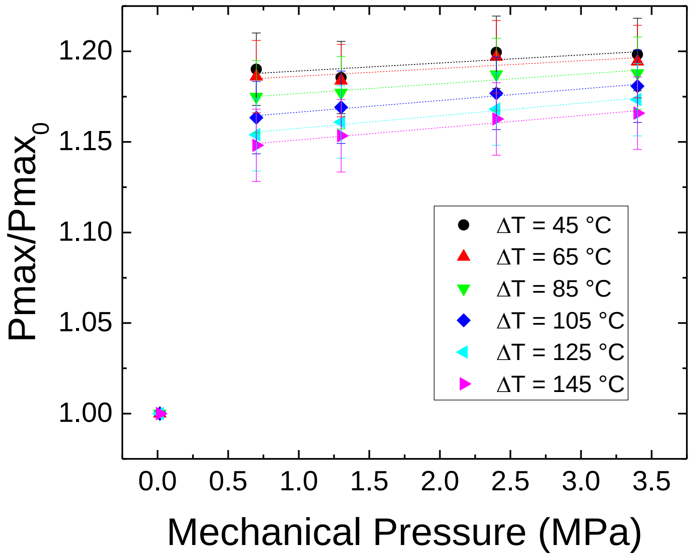
- Clamping pressure
- Thermal interface material (TIM)

Fabrication requirements:

- Flatness
- Parallelism
- Roughness



Thermal contact resistance



Clamping pressure > 1 MPa (~200Kg, 4x4 cm²)

- Safe pressure for the module
- Power non dependent on pressure (±1%)

Clamping pressure < 1 MPa (~200Kg, 4x4 cm)

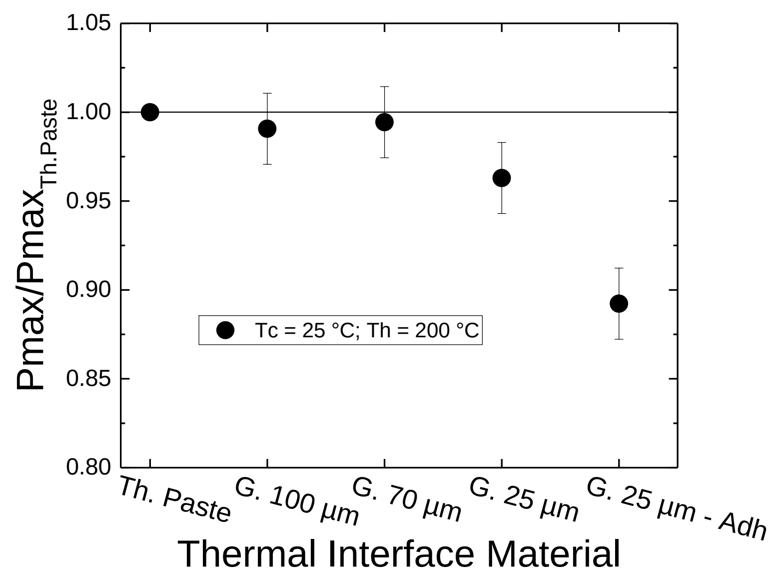
- ~ 14% reduction in Max. Power

Thermal Interface Material:

- Thermal paste: spread always identically
- Graphite paper: easier to reproduce!

Avoid adhesives:

- ~ 13% reduction in Max. Power



TE materials properties

Mean T and ΔT

Reference experiment

- T_c = 35 ºC
- T_h = 50 ºC - 170 ºC
- P ~ 2 MPa
- Graphite 70 µm

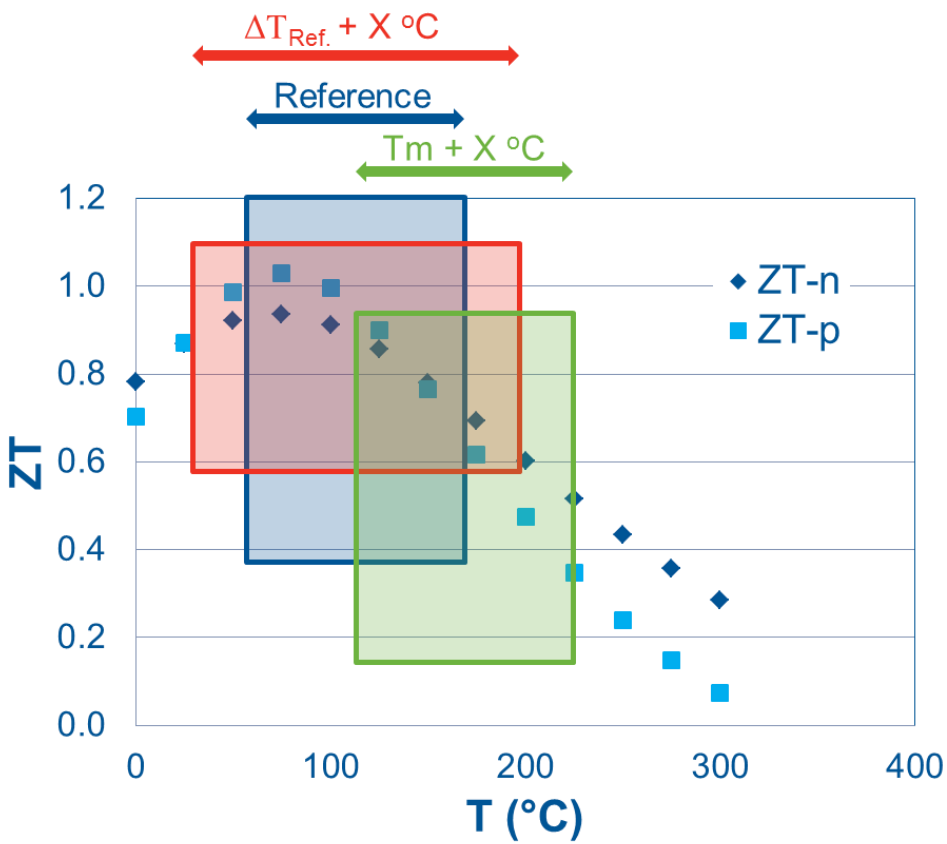
Different ΔT – Same mean T

- $T_m \sim T_{m,REF}$
- $\Delta T \sim \Delta T_{REF}$ + 15 ºC

Same ΔT – **Different mean T**

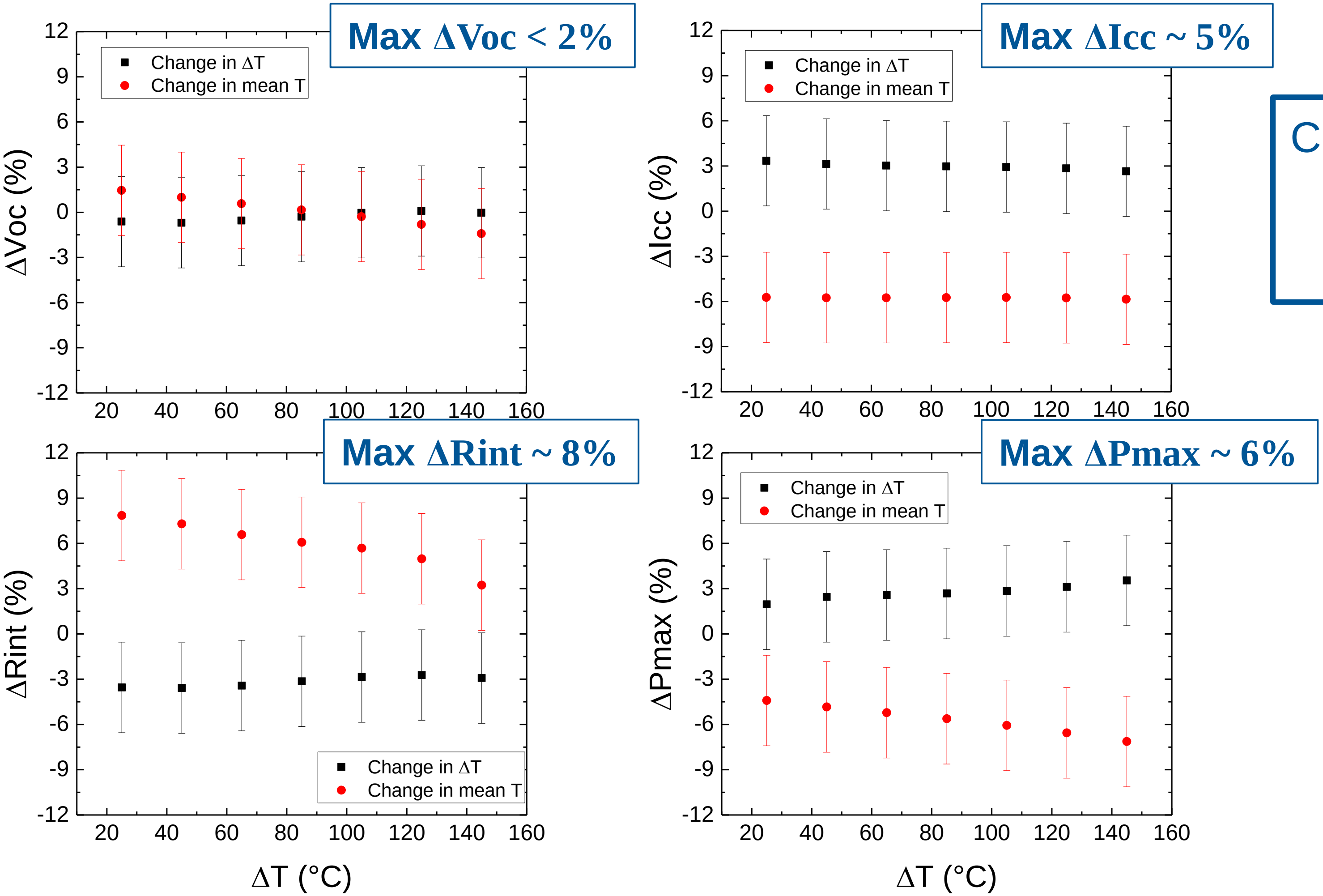
- $T_m \sim T_{m,REF}$ +15 ºC
- ΔT → no change

→ Equivalent to change T cold



TE materials properties

Mean T and ΔT



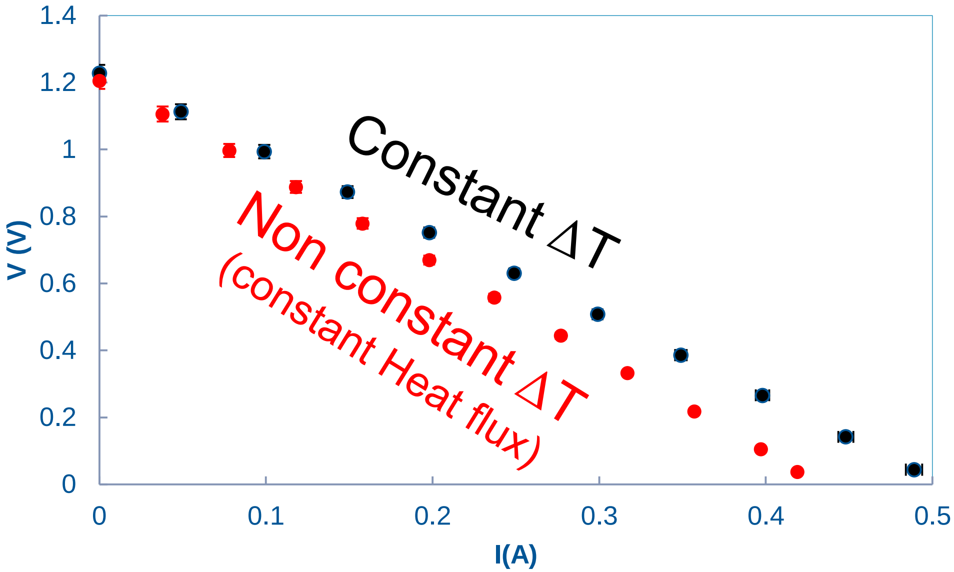
Change in:

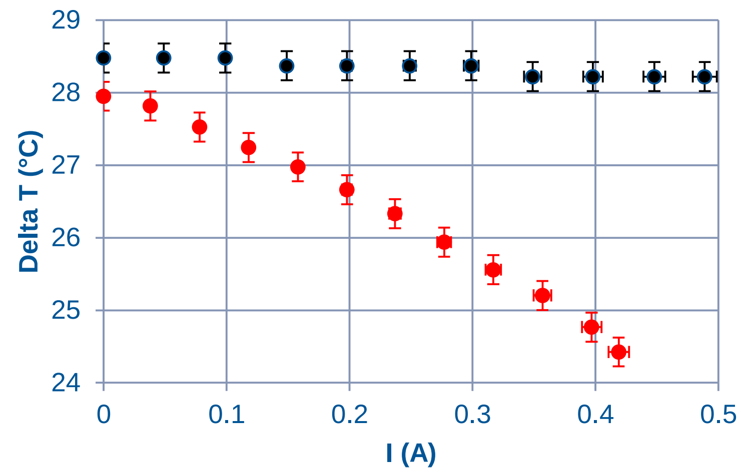
ΔT ~ 15 ºC

Tm ~ 15 ºC

TE materials properties

Constant Delta T during characterisation





Parameter	Constant T	Constant Heat Flux	Difference
Voc	1.23 V	1.21 V	1.6 %
Isc	0.51 A	0.44 A	15 %
Rint	2.43 Ω	2.79 Ω	15 %
Pmax	0.156 W	0.132 W	15 %

Working mode might depend on the application

Careful:
- Time per measurement
- Comparisons in round-robins

Combined Uncertainty

Measurement service: precision

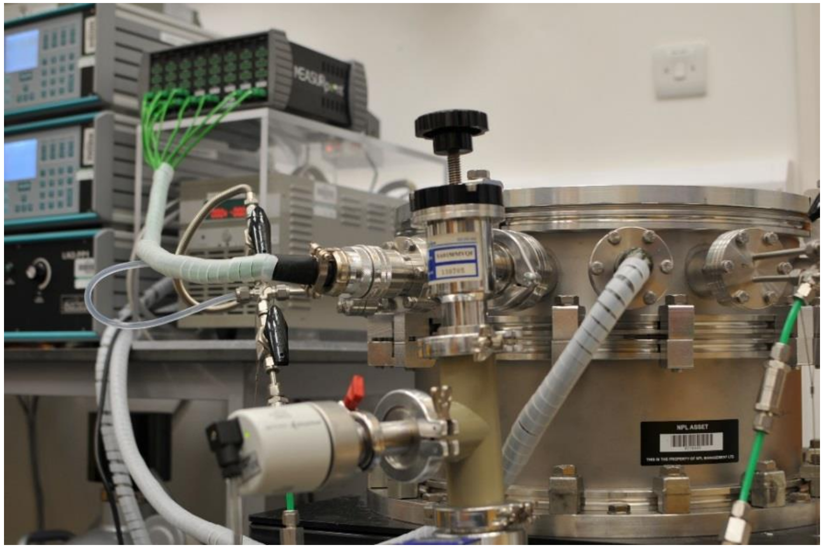
Repeatability	$u_c < 0.1\%$	Level of confidence: 1σ (68%)
Combined uncertainty:	$u_c = 2.9\ \%$	Level of confidence: 1σ (68%)
Extended uncertainty:	$U = 5.8\ \%$	Level of confidence: 2σ (95%)

Accuracy and validation:

- Use standards for calibration
- Round-robin among Institutions

Main sources of discrepancies:

- Interface material
- Clamping pressure
- Mean temperature (cold temperature)
- Constant ΔT during characterisation



CONCLUSIONS

- **International agreed method** to evaluate uncertainties (**GUM**)
- **Measurement service available at NPL** with a **repeatability < 0.1%**
- Main sources of uncertainty and discrepancies have been identified and discussed:
    - Clamping pressure
    - Interface material
    - Mean temperature and ΔT

Acknowledgments:

National Measurement Office

SolCell
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