Characterisation of thermoelectric generation modules: methods and uncertainties.

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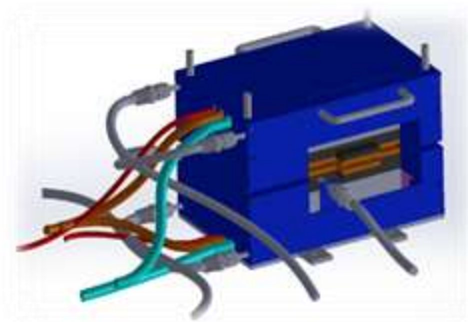
Module metrology

At NPL, we are developing facilities to measure **traceably** the performance of thermoelectric generators (TEG)



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“**Traceability**: the result can be related to a reference through a documented unbroken chain of **calibrations,** each contributing to the **measurement uncertainty”**

- **Precision: reproducibility**
- **Accuracy: “true value”**

Low accuracy
High precision

Higher accuracy
Low precision

High accuracy
High precision

Uncertainty: TEGs

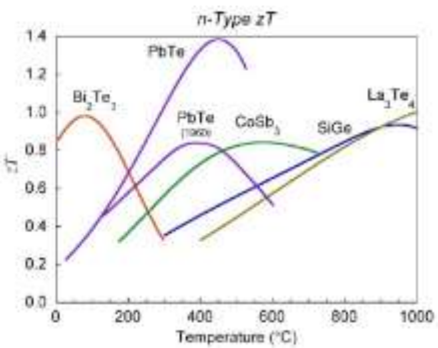
Sources of uncertainty for TEGs

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

TE materials properties

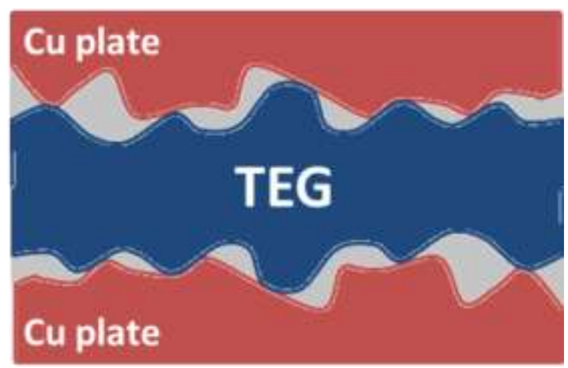
- Physical phenomena
  - Average T
  - T stabilisation
  - Meas. method

(const Heat Flux Vs. const T)



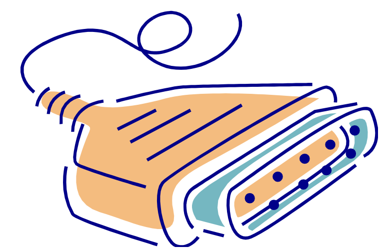
Thermal contact resistance

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



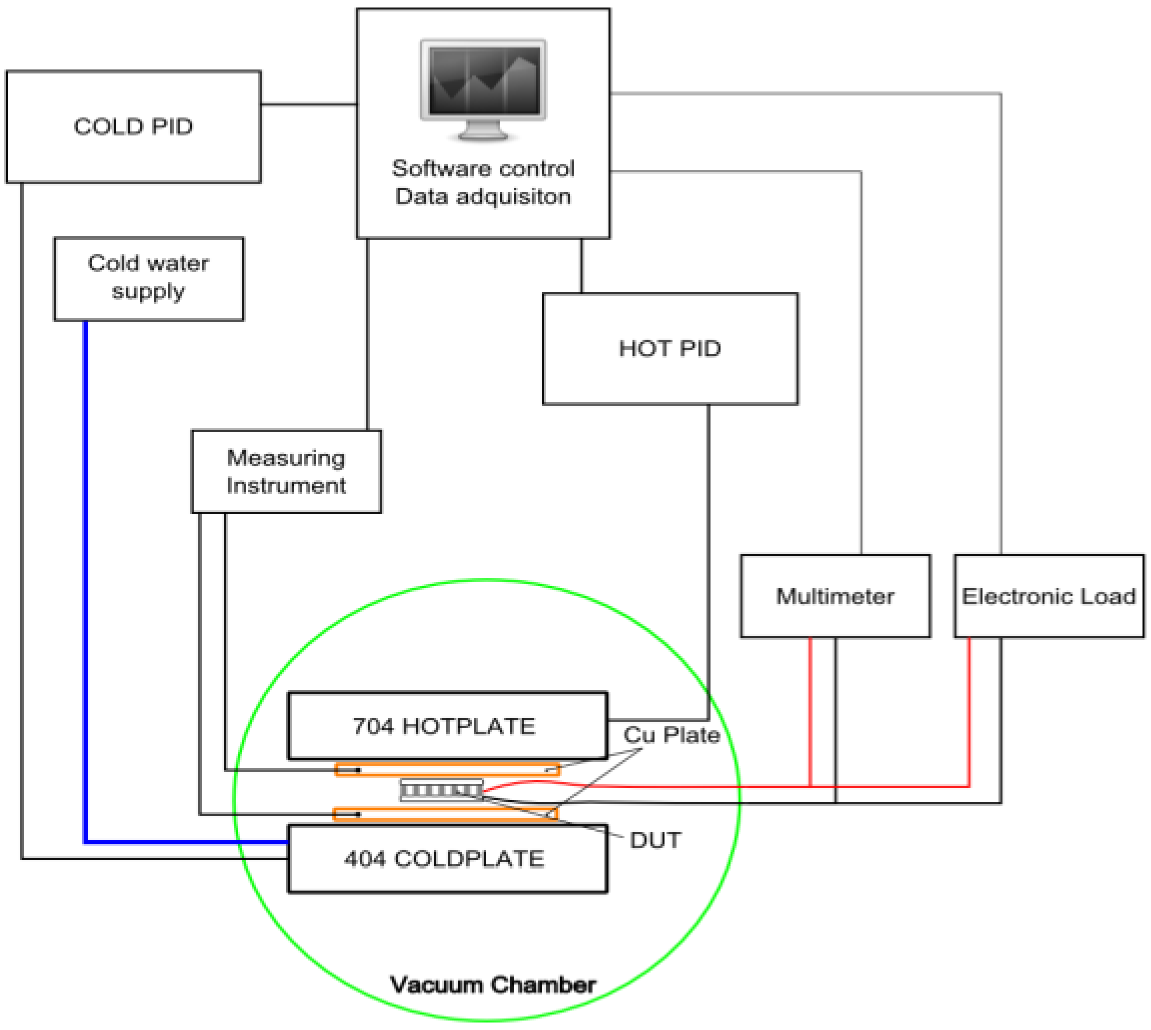
Data Acquisition

- Instrumental
  - Thermocouples
  - Electronic load
  - Multimeters

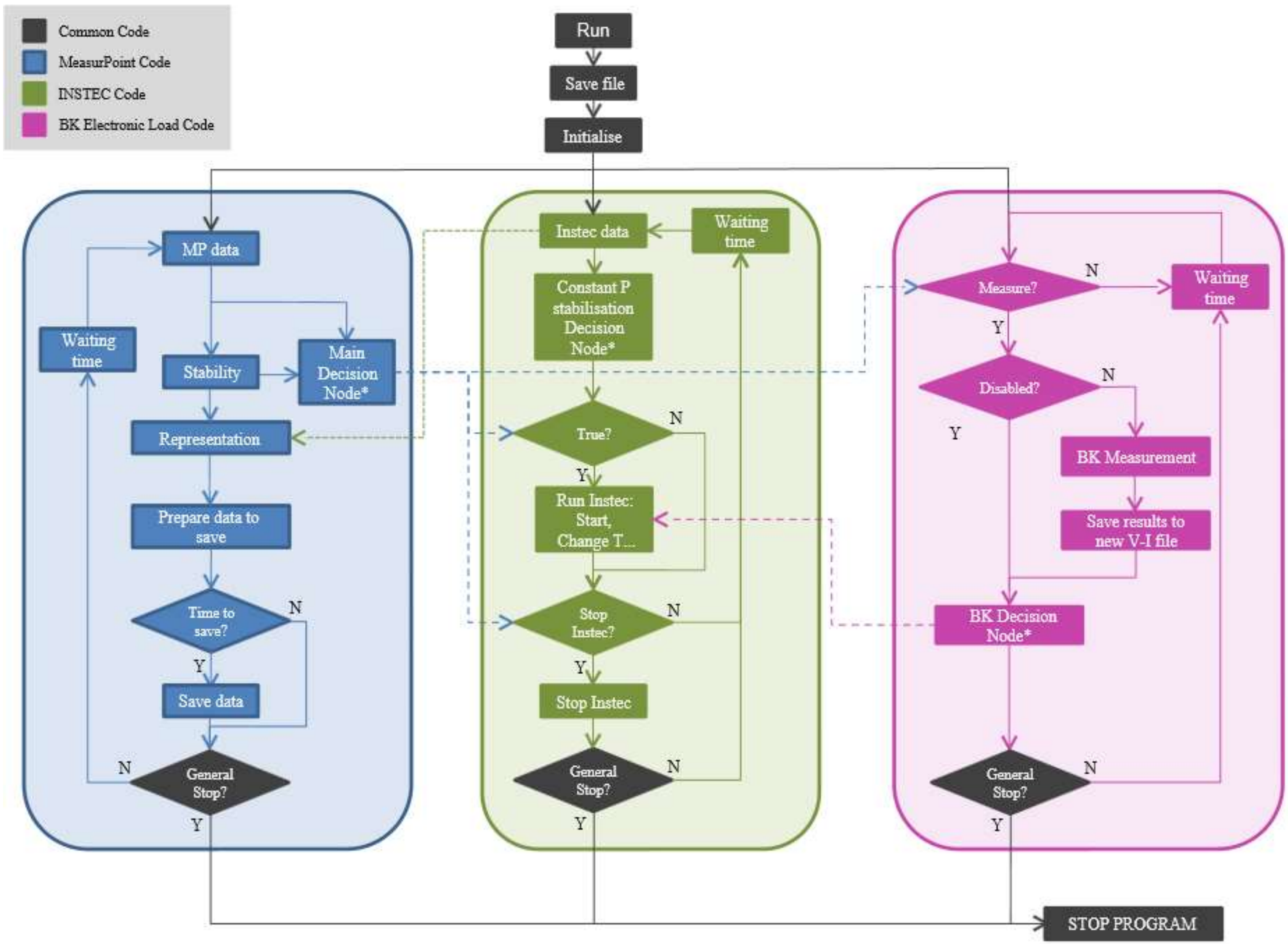


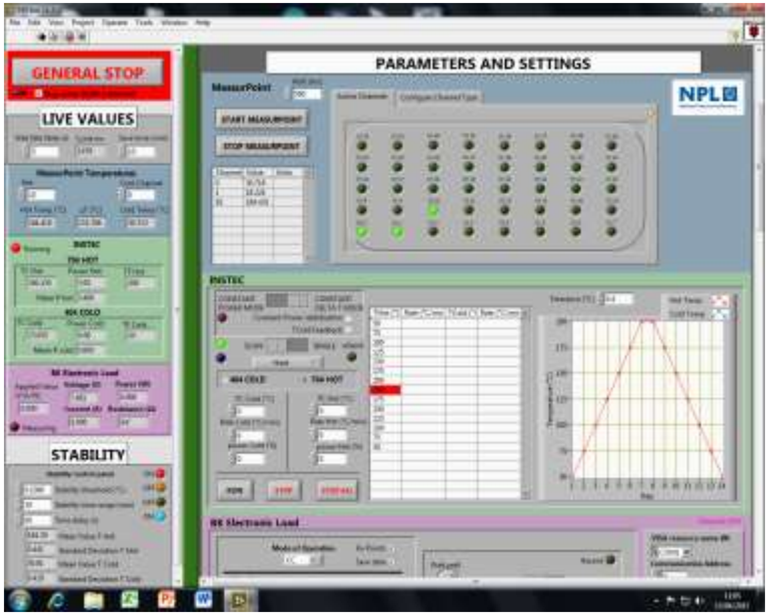
The main sources of uncertainty are those related to **materials properties** and **contact resistance**.

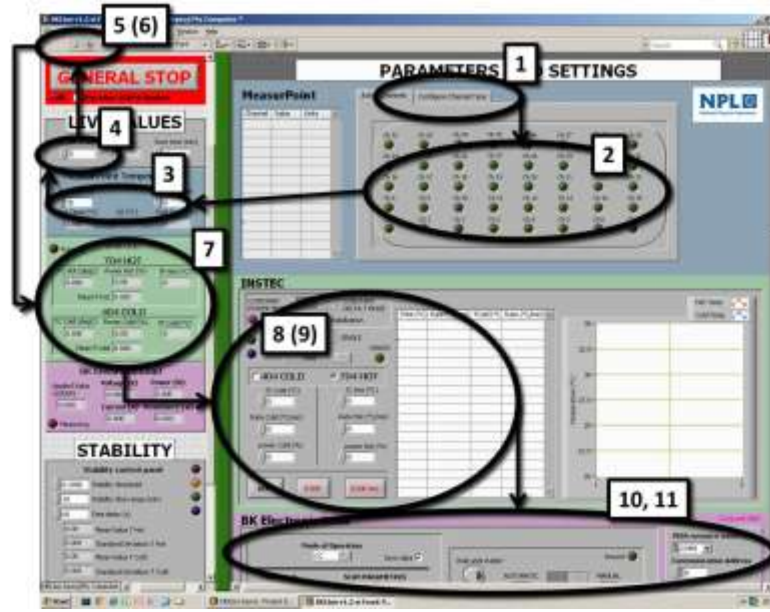
Measurement setup



Software flow chart




GENERAL STOP
LIVE VALUES
STABILITY
PARAMETERS AND SETTINGS
NPL
START MEASUREPOINT
STOP MEASUREPOINT
INSTEC
BK Electronic Load


5 (6)
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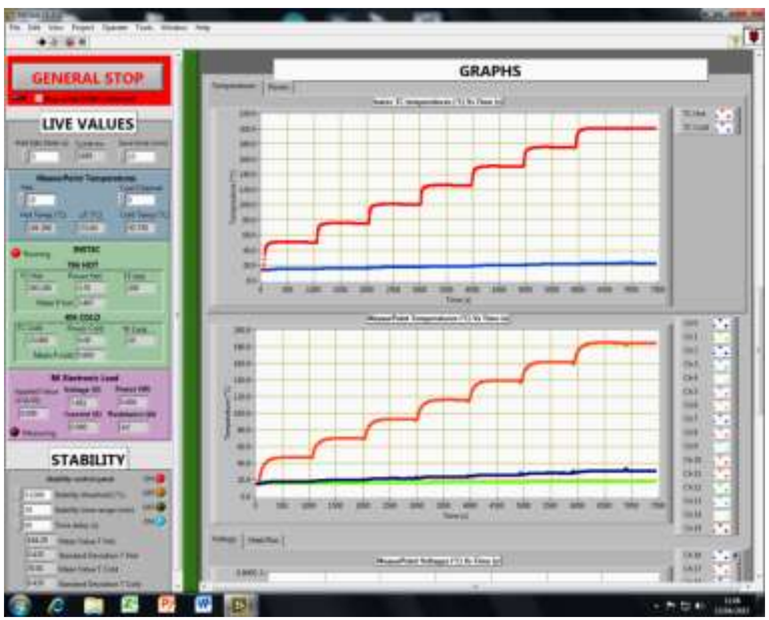
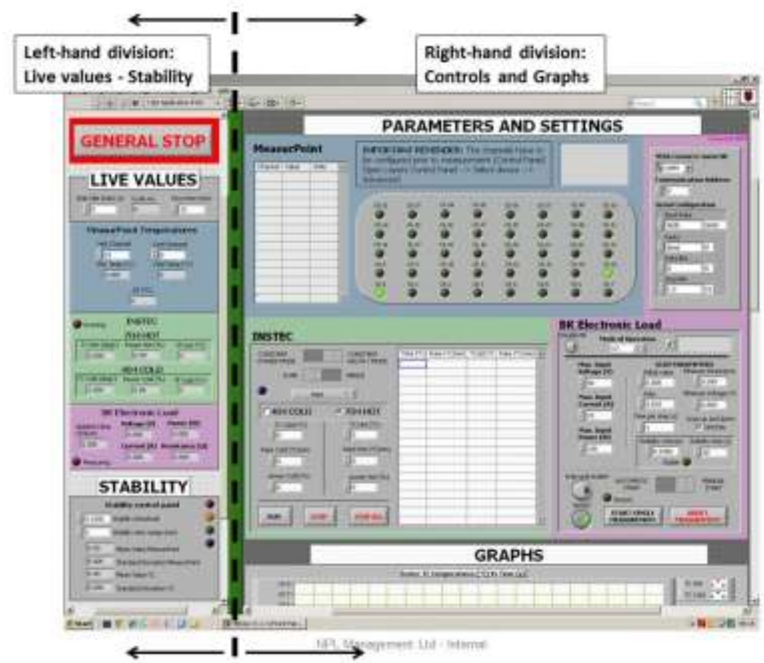
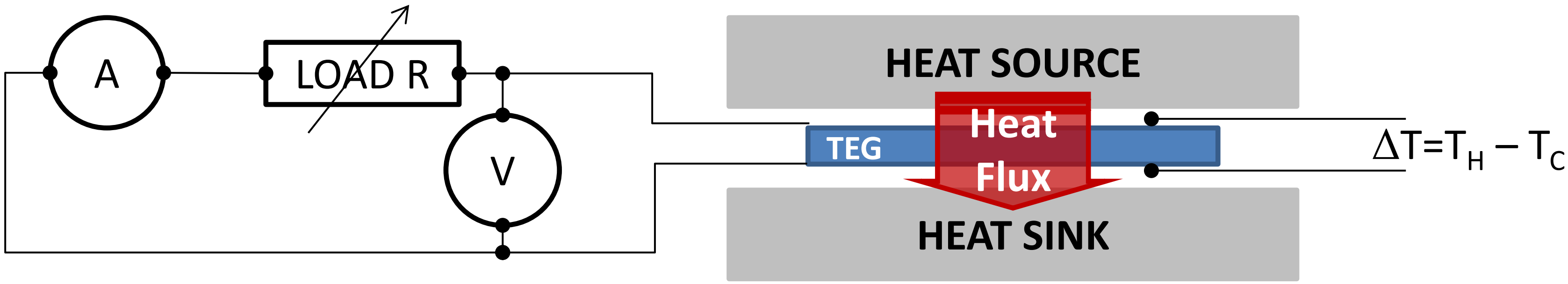
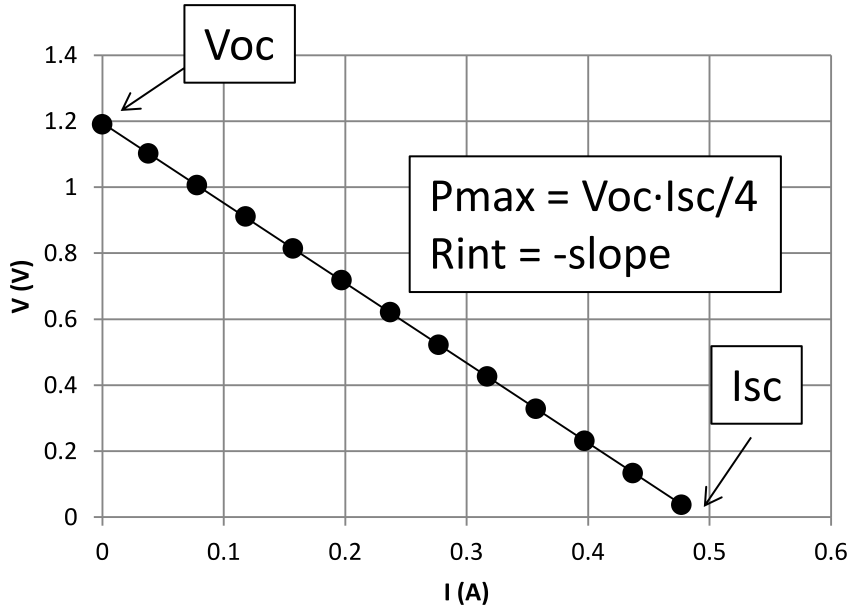
GENERAL STOP
PARAMETERS
SETTINGS
STABILITY
INSTEC
NPL

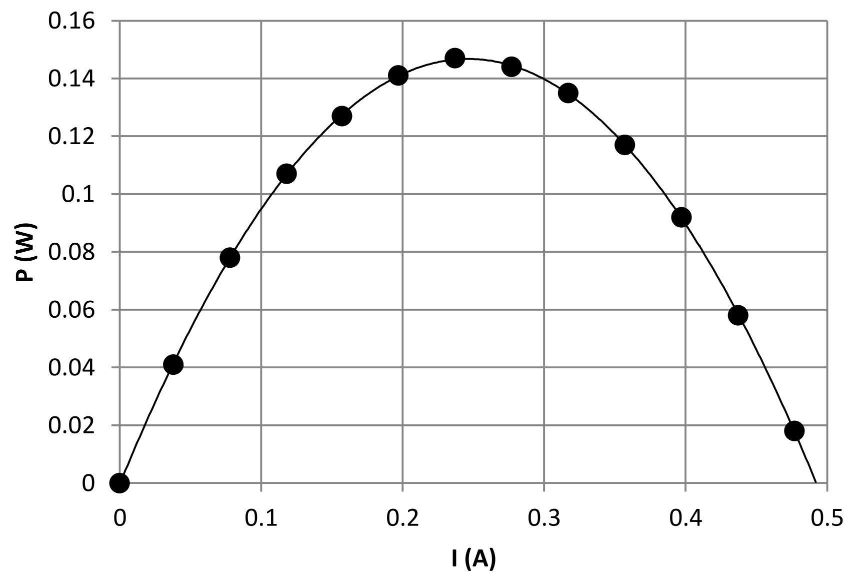

GENERAL STOP
LIVE VALUES
STABILITY
GRAPHS


Left-hand division:
Live values - Stability
Right-hand division:
Controls and Graphs
GENERAL STOP
LIVE VALUES
STABILITY
PARAMETERS AND SETTINGS
INSTEC
BK Electronic Load
GRAPHS

Material properties: How can they affect? →How is a TEG characterised?

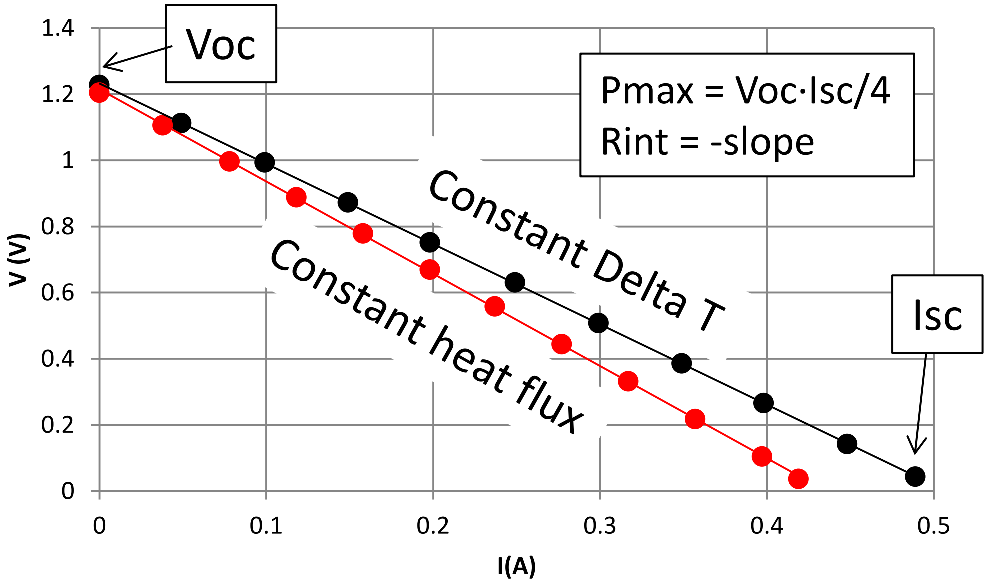


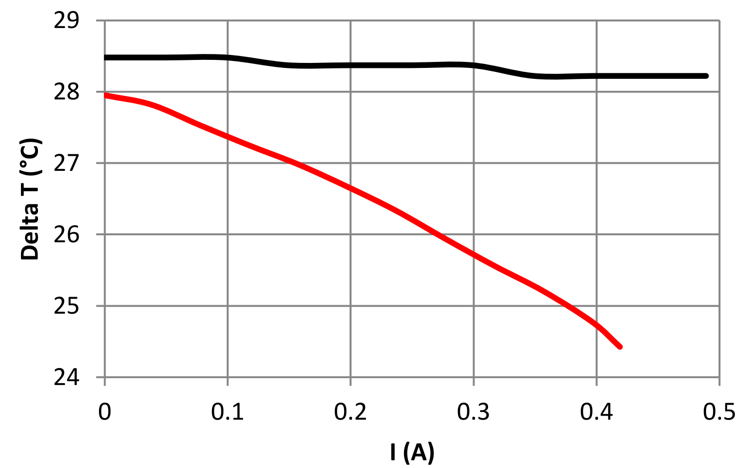




Constant heat flux Vs constant Delta T:

TEG works as a heat exchanger depending on the current



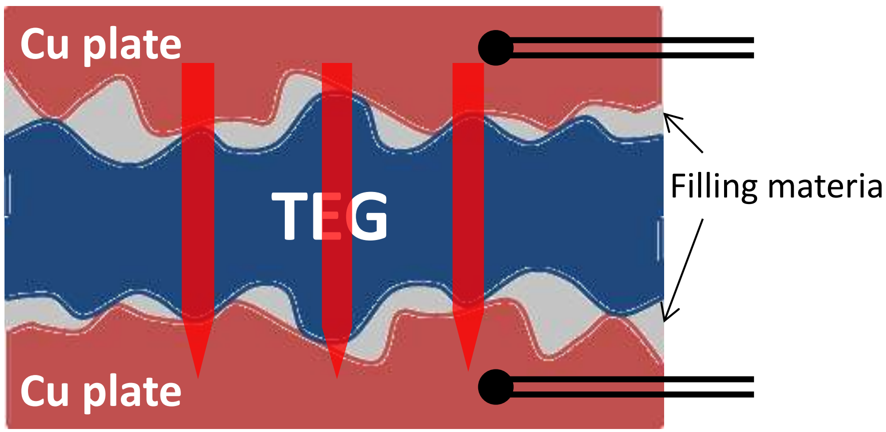


Parameter	Constant T	Constant Heat Flux	Difference
Voc	1.23 V	1.21 V	1.6 %
Isc	0.51 A	0.44 A	15 %
Rint	2.43 Ω	2.79 Ω	15 %
Pmax	0.156 W	0.132 W	15 %

Working mode might depend on the application

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

Thermal contact resistance

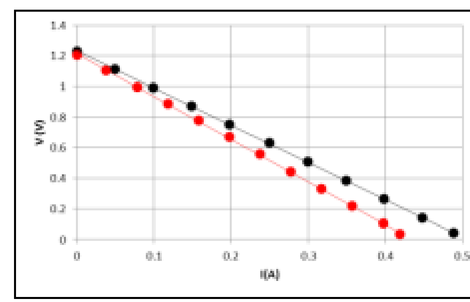


$$P \cdot R = \Delta T$$

$$R_T = R_{plate} + R_c + R_{TEG} + R_c + R_{plate}$$

What's the role of the contact resistance?

- Reduction of the heat flux → reduction of the efficiency
- False measurement of temperature
- Influence on characterisation results (Peltier effect)



Contact resistance →
- ○ Clamping pressure
- ○ Interface material

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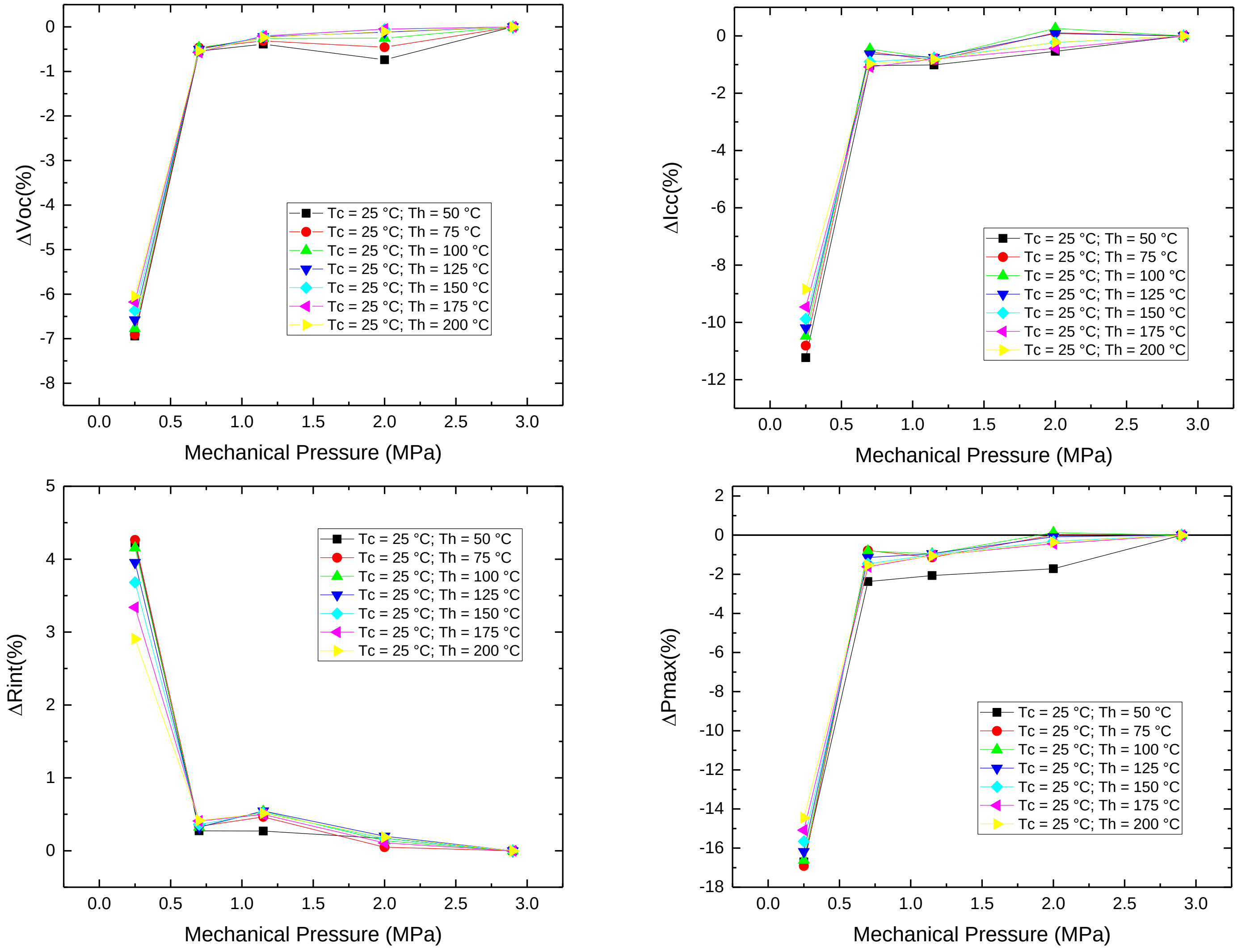
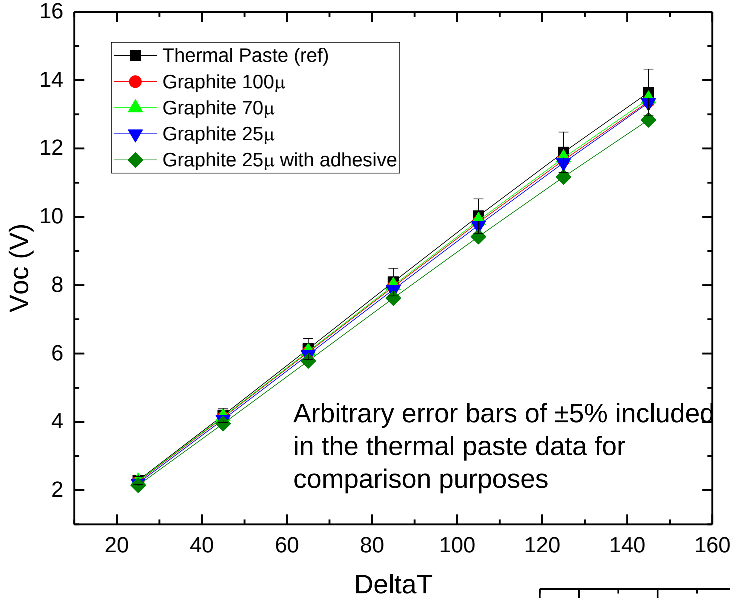
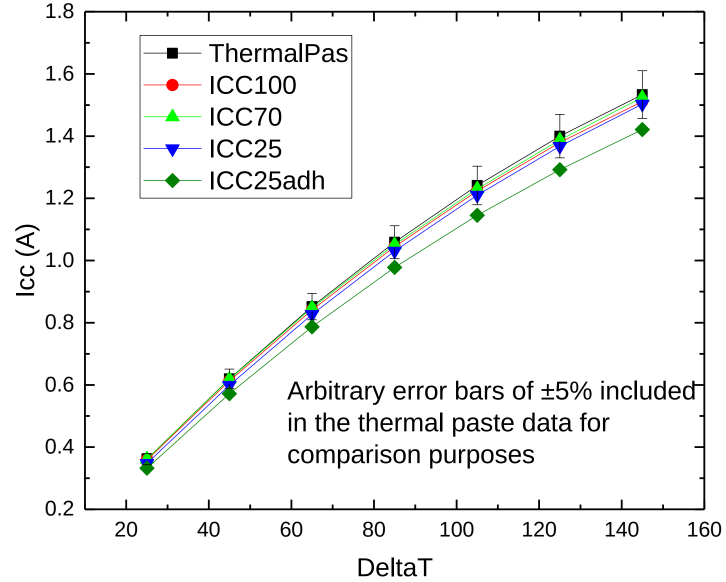
Clamping pressure:

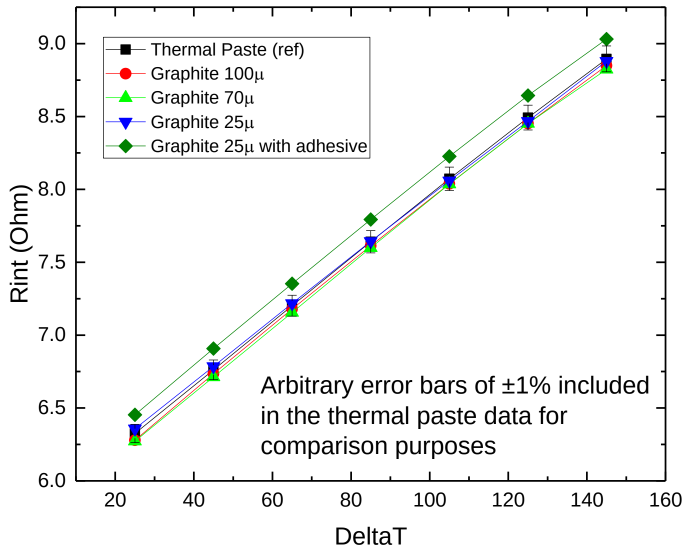
- Minimum pressure needed!



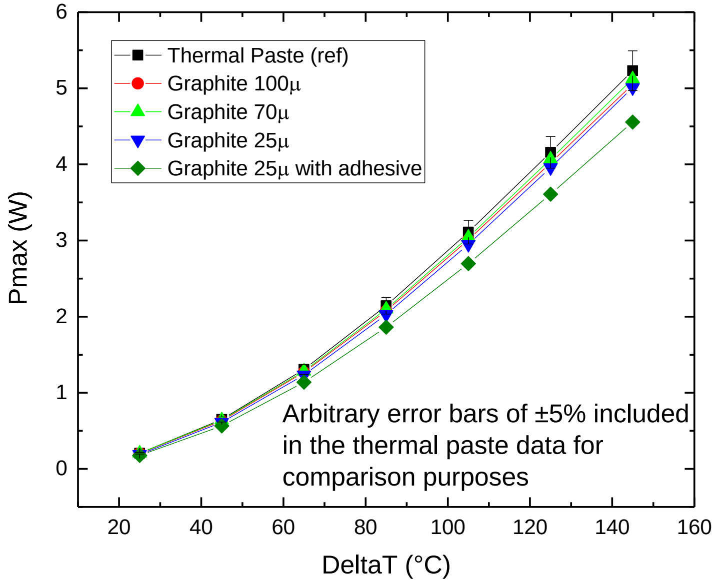
Interface materials: Thermal paste Vs Graphite paper



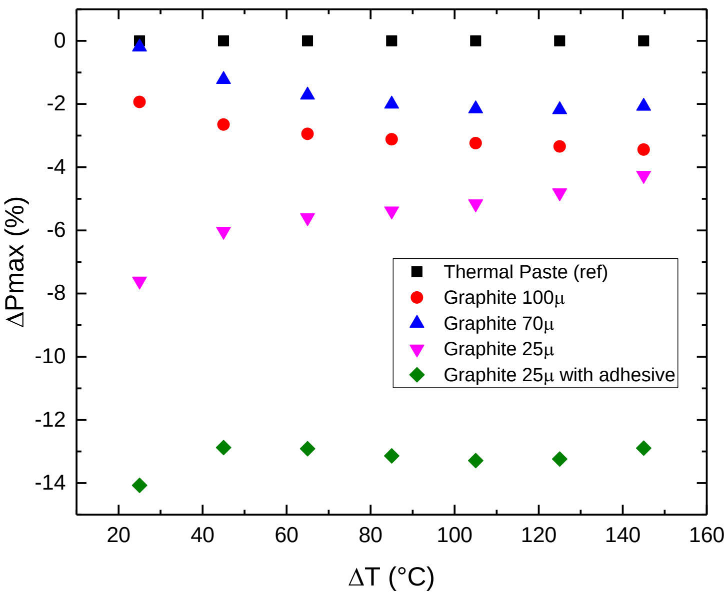




Interface materials: Thermal paste Vs Graphite paper



Relative change in maximum power output with different interface materials (with respect to thermal paste)



Thermal paste:

- Lower contact resistance
- High dependence on the thickness and homogeneity

Graphite paper: more reproducible results

Parameter	Voc	Isc	Rint	Pmax
Average difference	4 %	10%	5%	14%

Precision: reproducibility

Repeatability	$u_c = 0.1\%$	Level of confidence: 68%
Combined uncertainty:	$u_c = 2.9\ \%$	Level of confidence: 68%
Extended uncertainty:	$U = 5.8\ \%$	Level of confidence: 95%

Accuracy: traceability

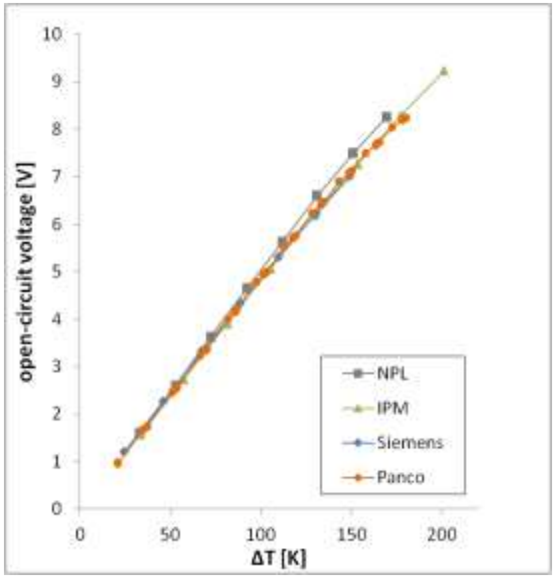
- Use standards for calibration
- Round-robin among Institutions

Sources of discrepancies:

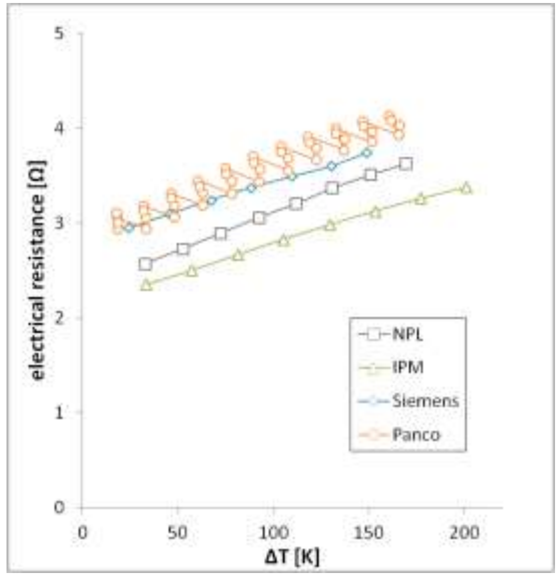
- Interface material
- Clamping pressure
- Constant heat flux or constant temperature
- Mean temperature (cold temperature)
- …

Comparison of module properties measurement

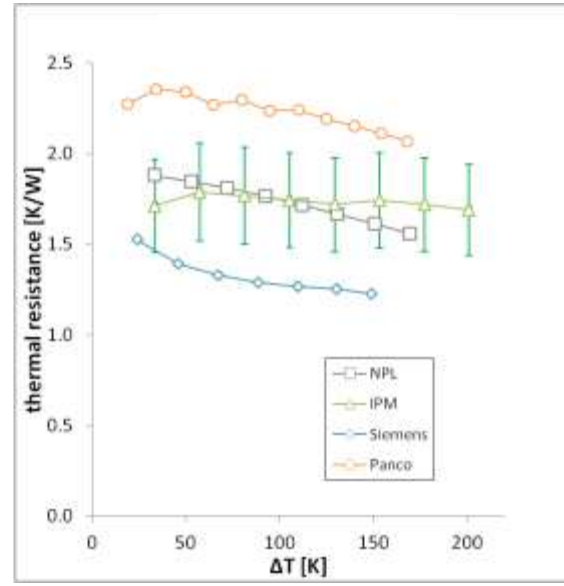
Open-circuit voltage



Internal electrical resistance



Thermal resistance



- Open-circuit voltage: Good agreement
- Internal electrical resistance: Unexpected scatter
- Thermal resistance: Expected scatter

Open NPL test bench for TE module conversion efficiency

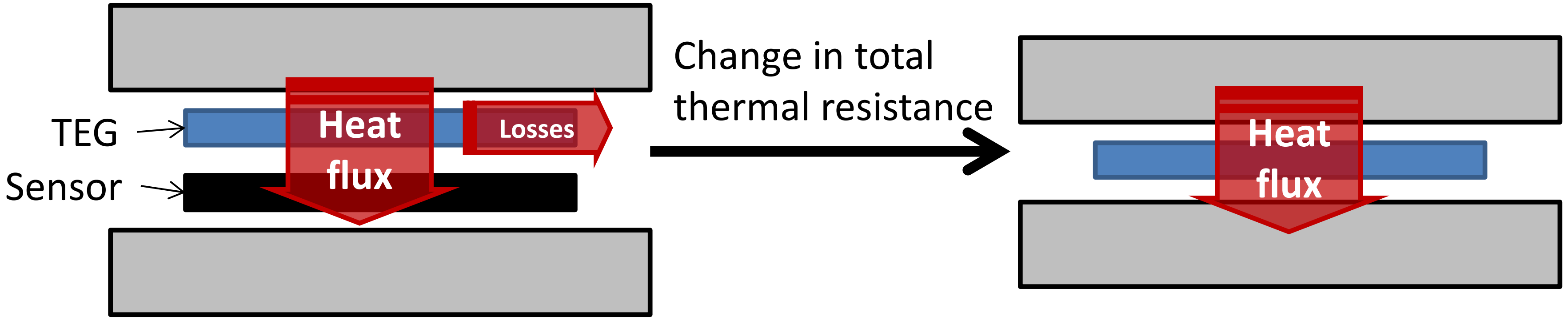
Siemens test bench for TE module conversion efficiency

Efficiency: measuring the heat flux

$$P \cdot R = \Delta T$$

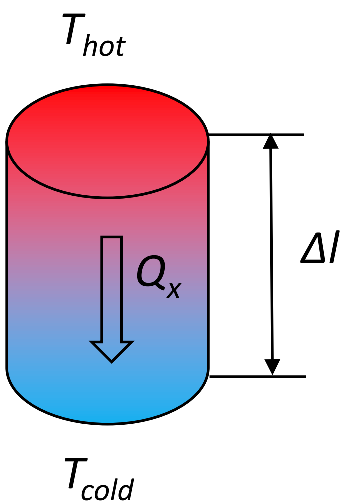
Heat flux sensor in series:

- Different total thermal resistance ➔ different heat flux,
- Loss of control of the temperature in the contact surface of the TEG



Discrepancies in efficiency of up to 20 %

▪ Thermal conductivity measurements



Q_x – amount of heat

Fourier's law for heat conduction:

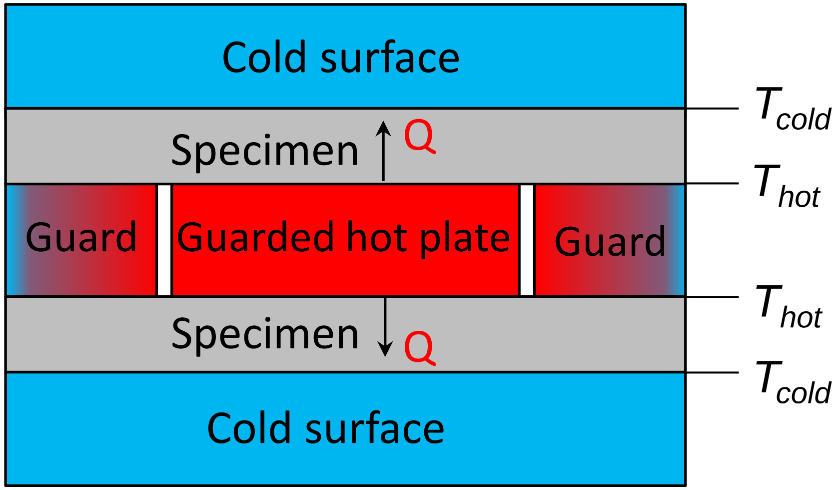
$$\frac{Q_x}{A} = -\kappa \frac{\partial T}{\partial x} = -\kappa \frac{\Delta T}{\Delta l}$$

Measurement of Q_x – primary source of error

Ways to measure Q_x:

- Directly (absolute methods)
- Indirectly (comparative methods)

Guarded Hot Plate (ASTM-C177, ISO 8302)



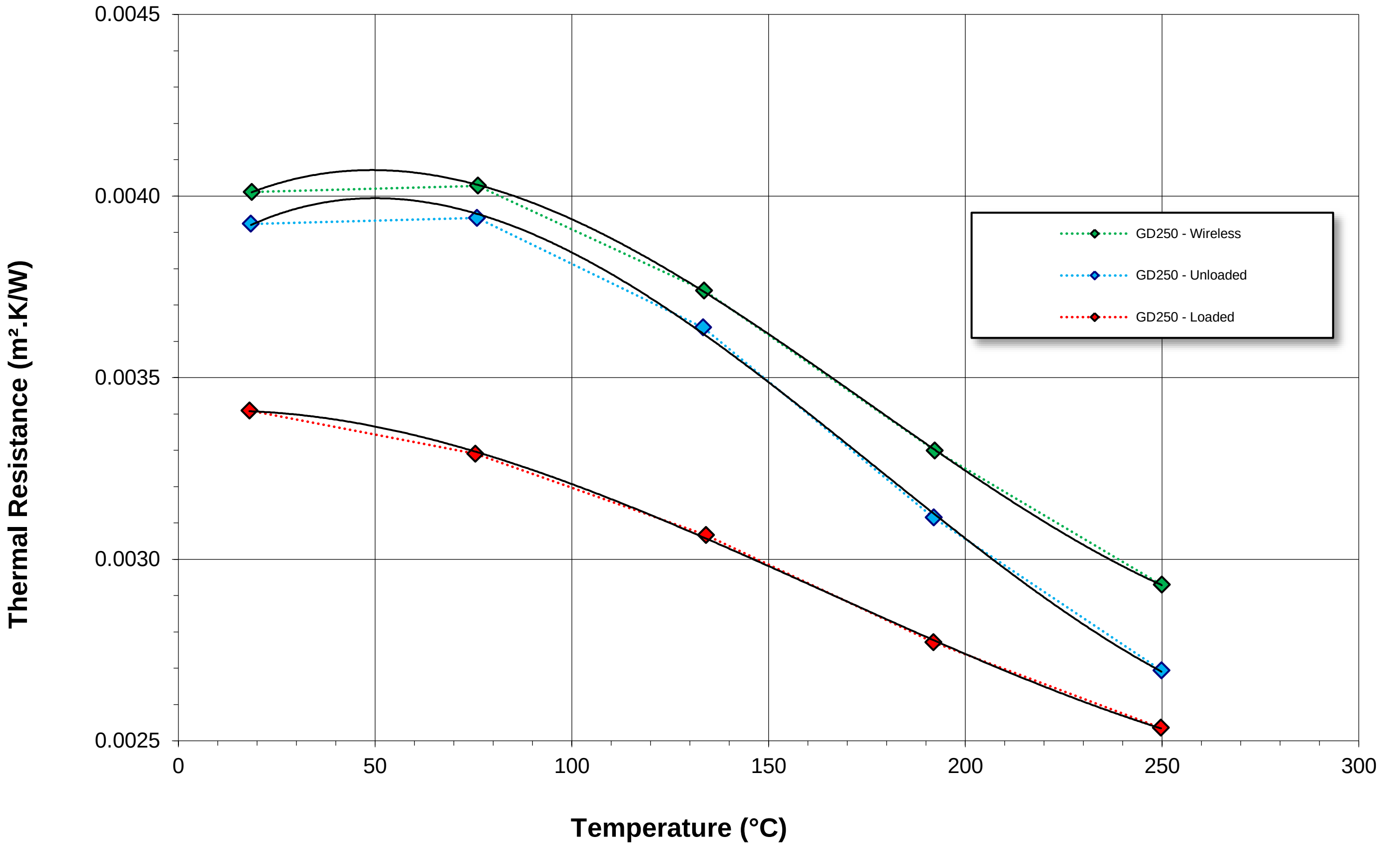
Uncertainty:

± 2% at RT

± 5% full operating range

- Specimen geometry: large ratio of area to thickness
- The guard heater limits the lateral heat flow
- Balancing the temperatures of the gap – main source of error
- Use of edge insulation and secondary guard at high T

Module thermal resistance



Guarded Hot Plate Single-Sided Mode (ASTM-C1044)

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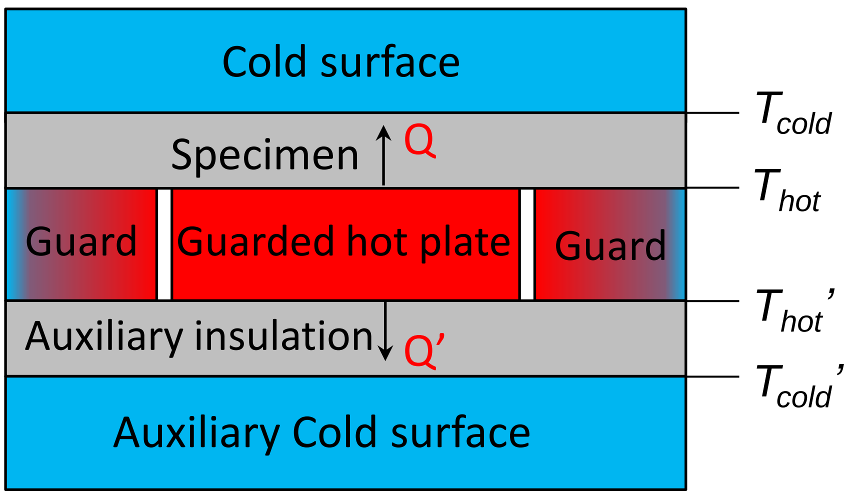


Uncertainty:

Slightly larger than double-sided mode

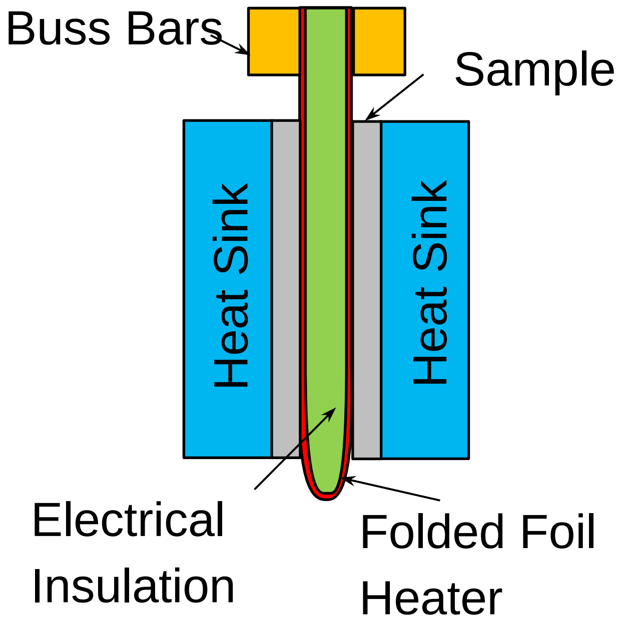
- Independent temperature control for T_{cold} and T_{cold}'

$T_{hot} = T_{hot}' = T_{cold}'$; $Q' = 0$ (principle)

$T_{hot} \approx T_{hot}' \approx T_{cold}'$; $Q' \approx 0 > 1\%$ (practice)

- Additional errors from balancing the gap if equipment was initially designed for double-side operation

Thin Heater Apparatus (ASTM-C1114)



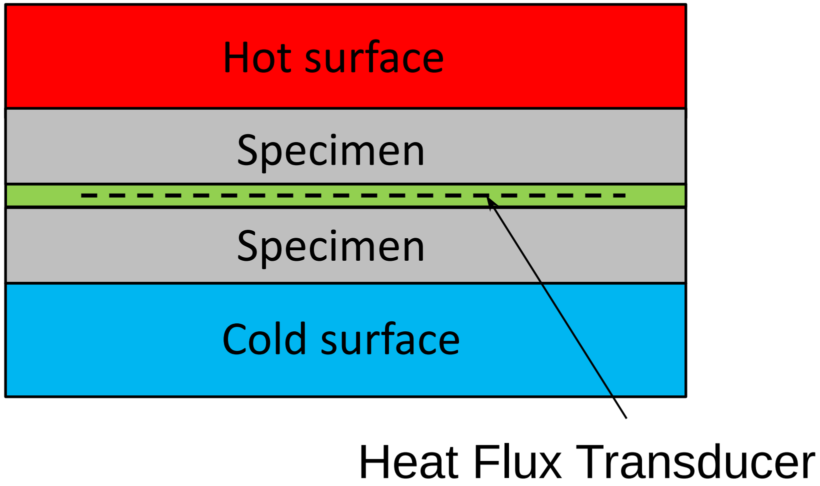
Uncertainty:

± 3% (300 – 550K)

- Low lateral thermal conductance of the heater avoids the need for insolation and the guard
- Steady-state is reached in shorter time than that of ASTM-C177

- Comparative methods

Heat flow meter apparatus (ASTM-C518)



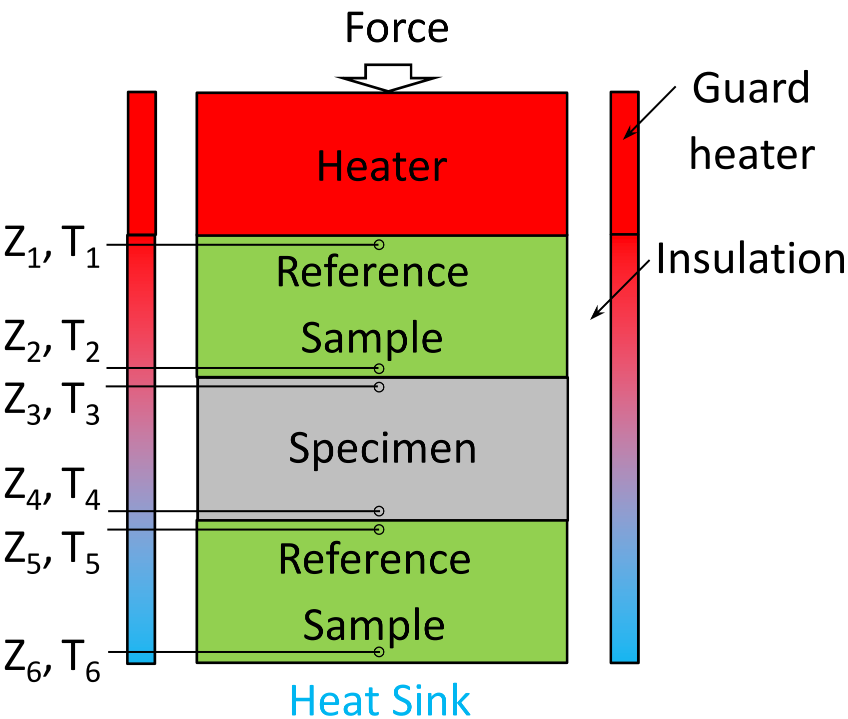
Uncertainty:

Within ± 2% of those determined by

Guarded Hot Plate method (ASTM-C177)

- Rapid, applicable to a wide range of test specimen
- Calibration of heat transducer required. To be calibrated with materials with similar thermal characteristics and thicknesses as the materials to be evaluated

Guarded Longitudinal Heat Flow (ASTM-E1225,-D5470)



$$\kappa = \frac{Z_4 - Z_3}{T_4 - T_3} \cdot \frac{\kappa_{ref}}{2} \cdot \left(\frac{T_2 - T_1}{Z_2 - Z_1} + \frac{T_6 - T_5}{Z_6 - Z_5} \right)$$

- No heat flux measurements required
- Reference bars with similar thermal characteristics and cross-sections as the materials to be evaluated
- $\kappa_{ref} > 50$ W/mK

Uncertainty: How?

How:

- Identify sources of uncertainty
- Obtain their contributions: distribution probability (normal, triangular, square...)

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

x_j → n-values

Normal distribution

$$\bar{x} = \frac{\sum_i x_i}{n} \qquad s(\bar{x}) = \frac{s(x_i)}{\sqrt{n}} \equiv u(x_j)$$

$$\left(s(x_i) = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n-1}} \right)$$

Rectangular distribution

$$u(x_i) = \frac{a_i}{\sqrt{3}} \qquad a_i \equiv semi - range$$

Others

$$u(x_i) = \cdots$$

- Obtain combined uncertainty: level of confidence

Combined uncertainty:

$$u_c(y) = \sum_j c_j{}^2 u^2(x_j) \equiv \sum_j u_j(y)$$

Standard deviation ➔ 68% confidence

⟶

Expanded uncertainty:

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

k=2 ➔ (95% confidence)

Uncertainty contributions (for precision)

Parameter	Repeatability	Clamping Pressure (3 MPa < P < 12 MPa)	Interface material	Mean T (during V-I)	Temperature stability	Instruments
Uncertainty contribution to Power Output	< 0.1 %	< 0.3 %	< 0.2 %	< 0.8 %	< 0.5 %	< 1.0 %

CONCLUSIONS

- Facility to characterise thermoelectric modules has been built at NPL with a power output repeatability of 0.1%.
- Main sources of uncertainty and discrepancies have been identified and discussed:
    - Mean temperature
    - Const Heat Flux Vs Const Delta T
    - Interface material
- Heat flux measurement has higher uncertainty.
- A complete uncertainty study is being done.