National Physical Laboratory

Heat Flux Measurements

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Thermoelectric Network Meeting

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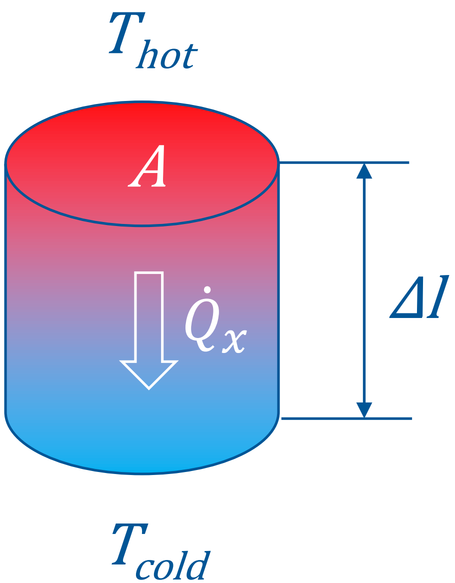
Thermal conductivity

National Physical Laboratory

Why κ is so hard to measure?



Fourier's law:

$$\frac{\dot{Q}_x}{A} = -\kappa \frac{\partial T}{\partial x} = -\kappa \frac{\Delta T}{\Delta l}$$

- Heat transfer is hard to isolate
- Ideal TE: $\kappa_{specimen} \sim \kappa_{air}$
- κ varies little with temperature, material composition, etc.

Up to 20% data variation from inter-laboratory round-robin

Wang et al. *J. Elect. Mat.* **42**, 1073 (2013)

Thermal conductivity

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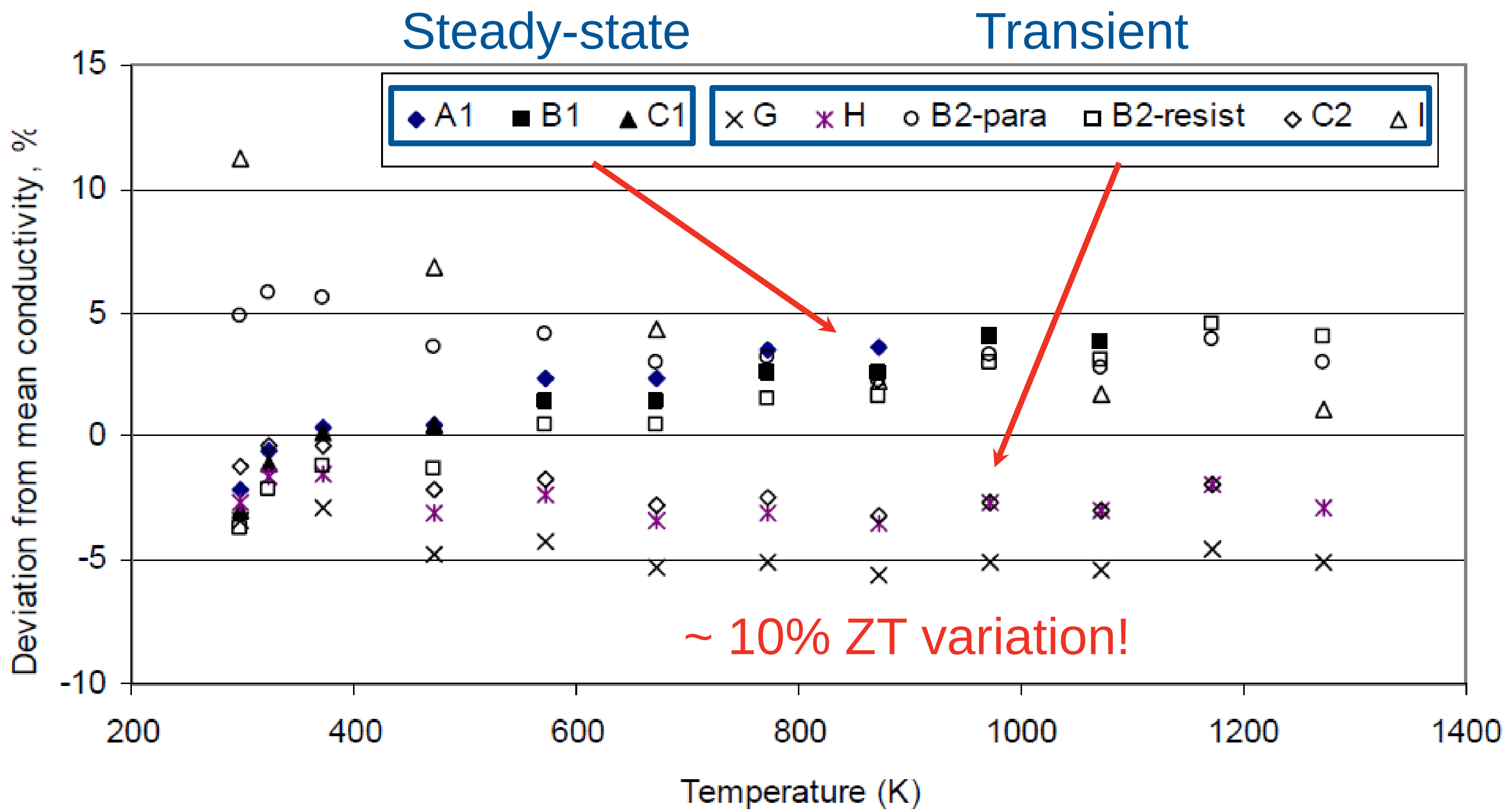
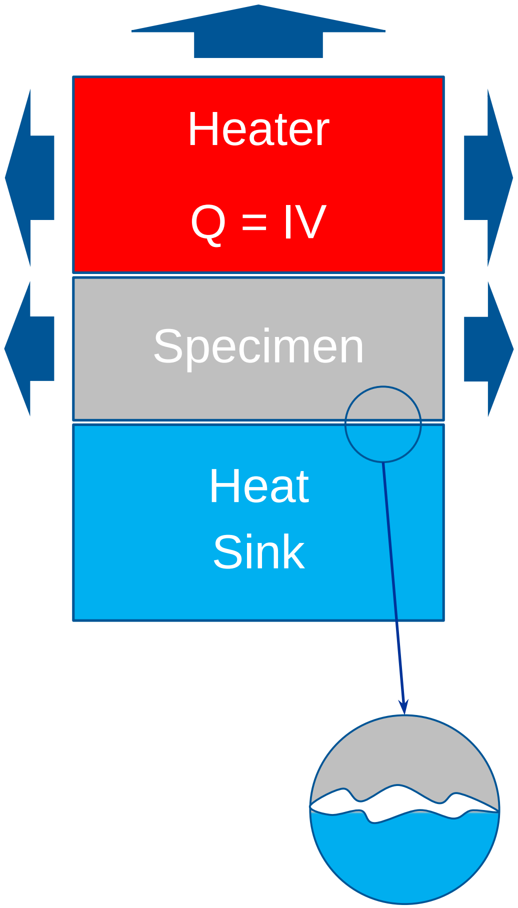
Deviation from mean κ for BCR-724 for different laboratories



Source: D. Salmon *et al.* "Certification of thermal conductivity and thermal diffusivity up to 1025 K of a glass-ceramic reference material BCR-724" (2007)

Sources of error

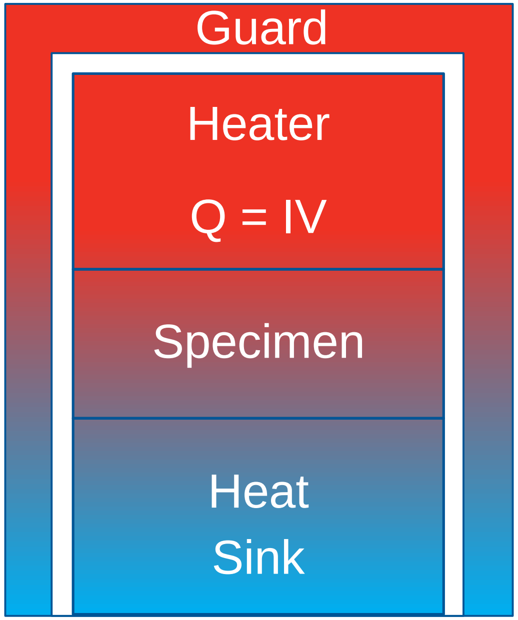


- Steady state methods
  - Parasitic heat conduction paths
    - Q ≠ IV
    - Heat flow not 1D
  - Thermal contact resistance
- Transient methods (3ω, optical)
  - Measure thermal diffusivity
  - Different sources of uncertainty

Review of Measurement methods
Direct heat flux measurement

Ideal solution for large samples

- Guarded Hot Plate (ASTM-C177, ISO 8302)



- Advantage
  - Lowest uncertainty

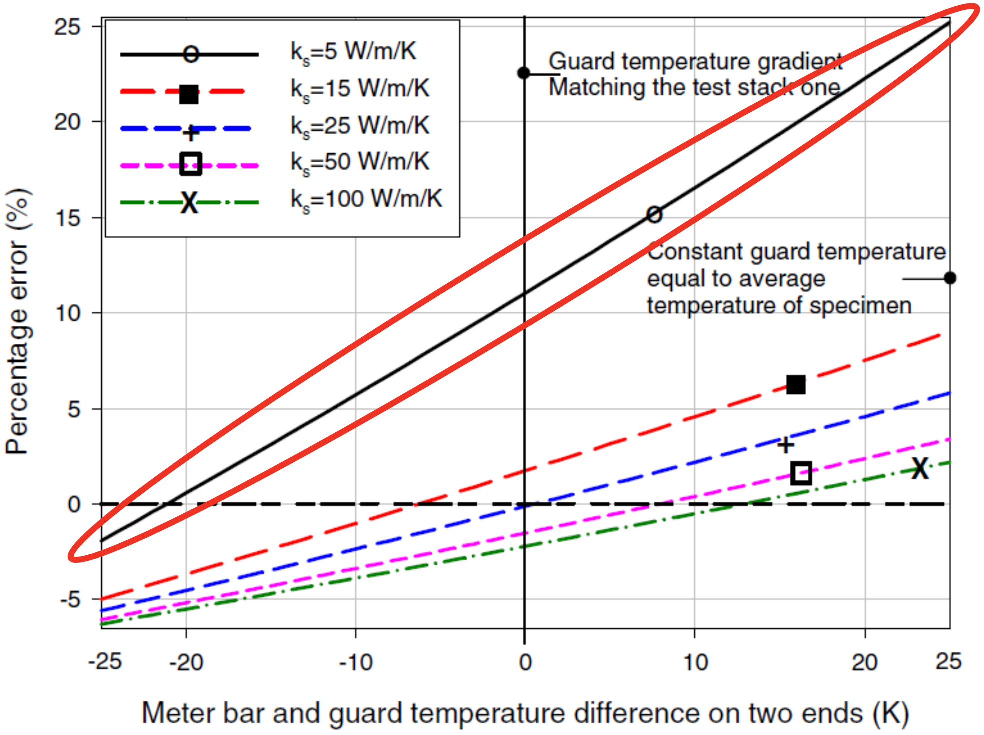
  ± 2% (RT)

  ± 5% (full T range)
- Disadvantage
  - Temperature control
  - Calibration

Contact: thermal_enquiries@npl.co.uk

Guard temperature balance challenge

- Small temperature mismatch – large errors!



Two practical guard operational modes considered:

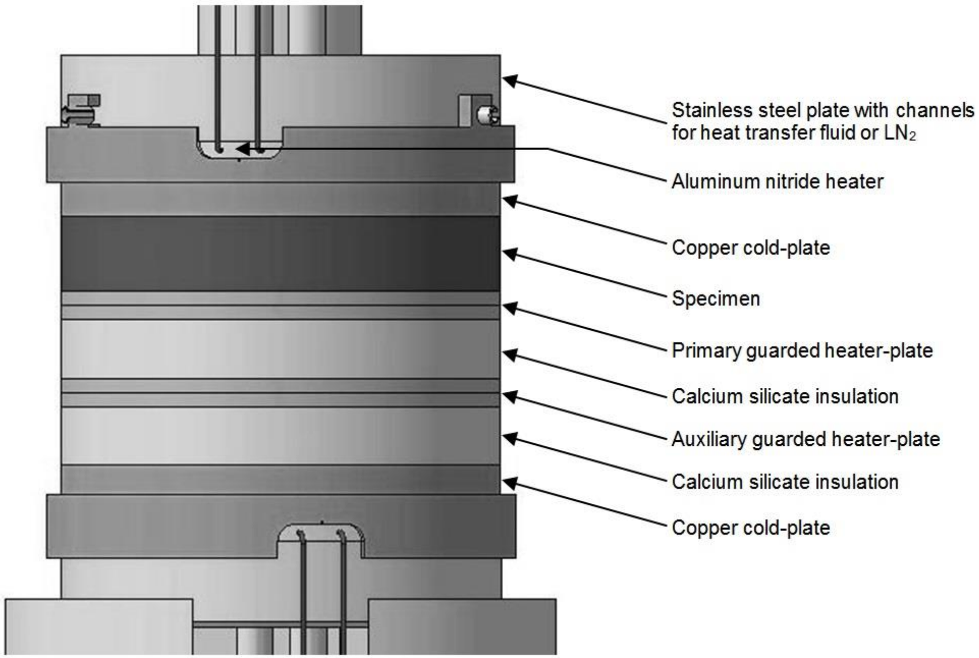
$T_{guard} = T_{mean}$

$\Delta T_{guard} = \Delta T_{stack}$

Source: C. Xing *et al.* Meas. Sci. Technol. **22** (2011)

Example of best practice

- NPL's Guarded Hot-Plate



Temperature: - 100 … 250° C

Specimen: Ø 50.8 – 75 mm,
1 – 20 mm thick

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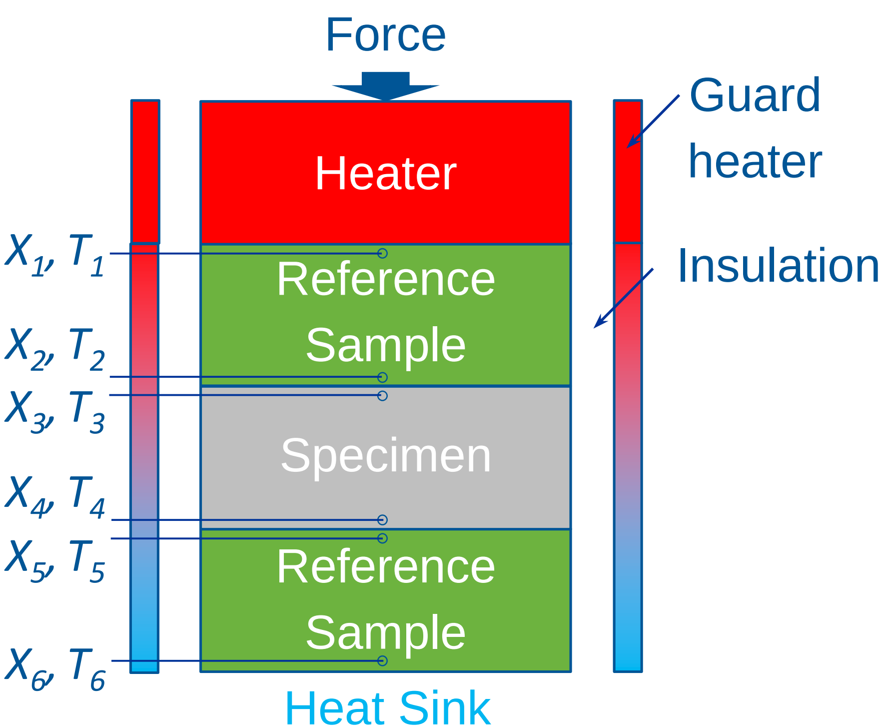
Review of Measurement methods
Indirect heat flux measurement

Practical solution for wide range of samples

- Comparative Cut Bar (ASTM-E1225)

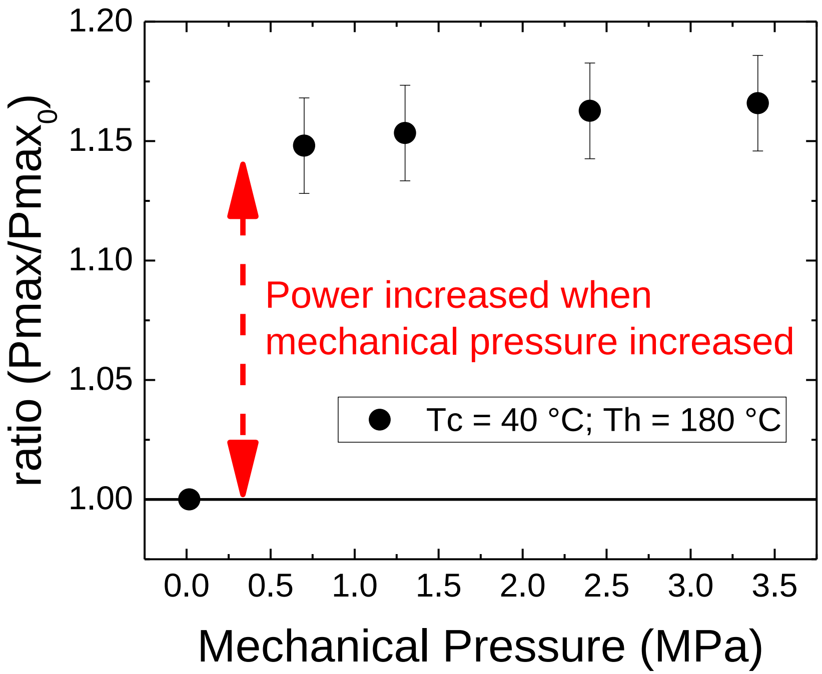


$$\kappa = \frac{X_4 - X_3}{T_4 - T_3} \cdot \frac{\kappa_{ref}}{2} \cdot \left(\frac{T_2 - T_1}{X_2 - X_1} + \frac{T_6 - T_5}{X_6 - X_5} \right)$$

- Advantage
  - Versatile
- Disadvantage
  - Higher uncertainty (up to 18%)

Thermal contact resistance varies greatly up to threshold pressure

- Mechanical pressure



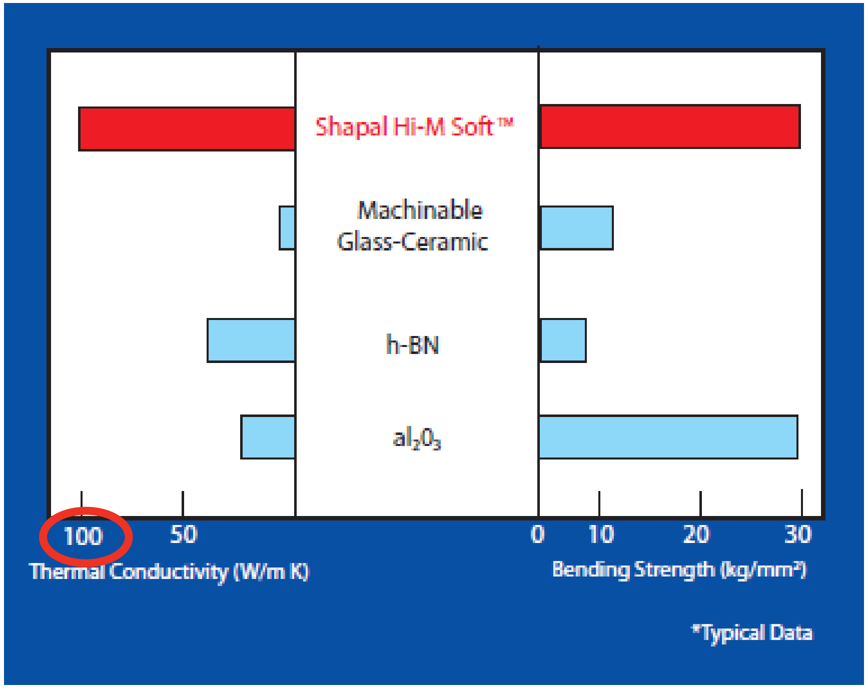
Clamping with bolts = very high pressure with little effort

Variation in TEG power output minimized when $P \geq 1$ MPa

Choice of reference bar material

- κ > 50 W/mK (ASTM-D5470)
- Mechanical strength
- Chemical stability

⇨ BN/AlN "Shapal"

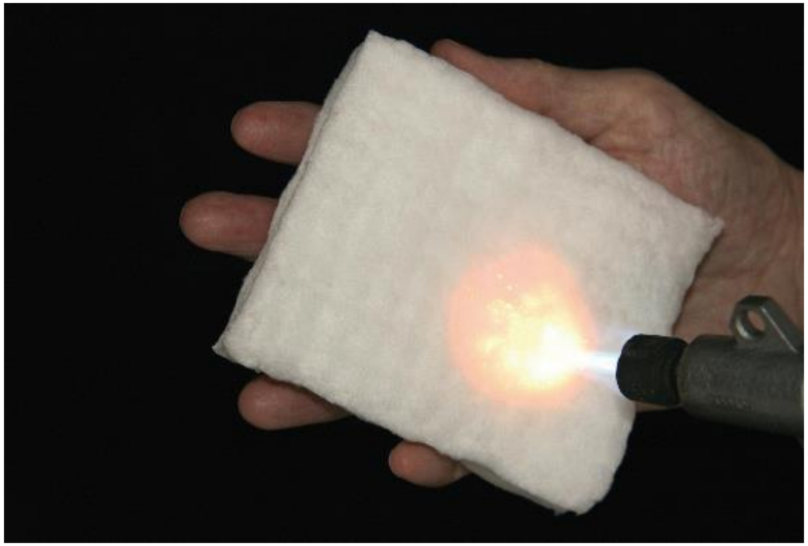


Source: http://www.precision-ceramics.co.uk/

Insulation vs lateral guard

- Insulation material
  - Low κ
  - Chemical stability
  - Easy to handle

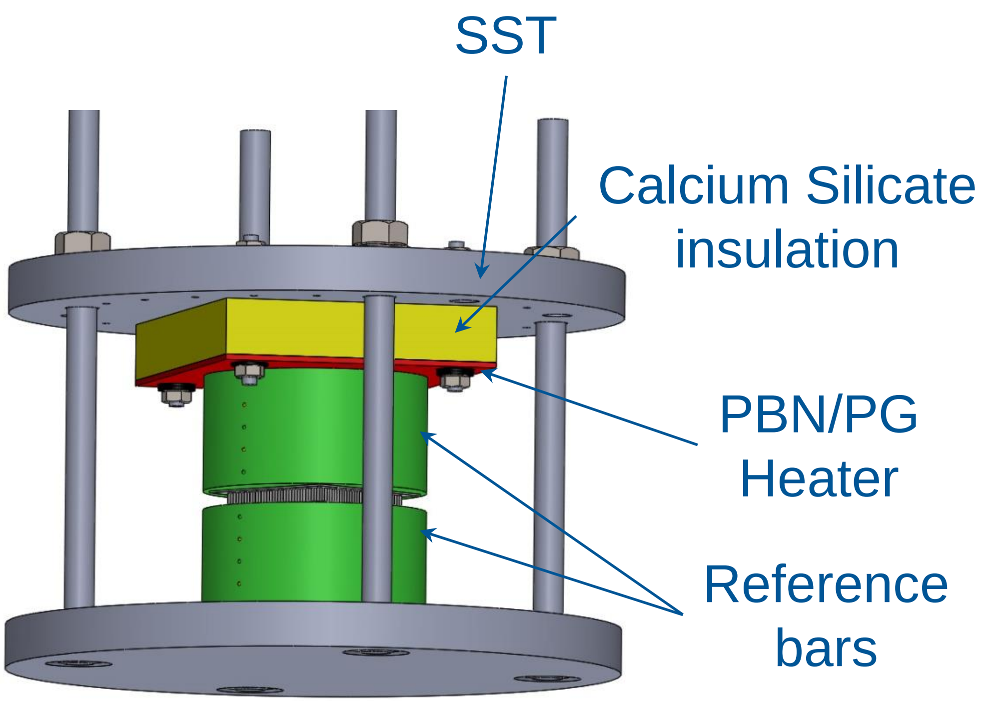
⇒ Ceramic Fiber Blanket "Superwool® 607 HT"



- κ = 0.04 – 0.48 W/mK
- Non-hazardous (bio-degradable)

Source: http://www.precision-ceramics.co.uk/

Experimental setup

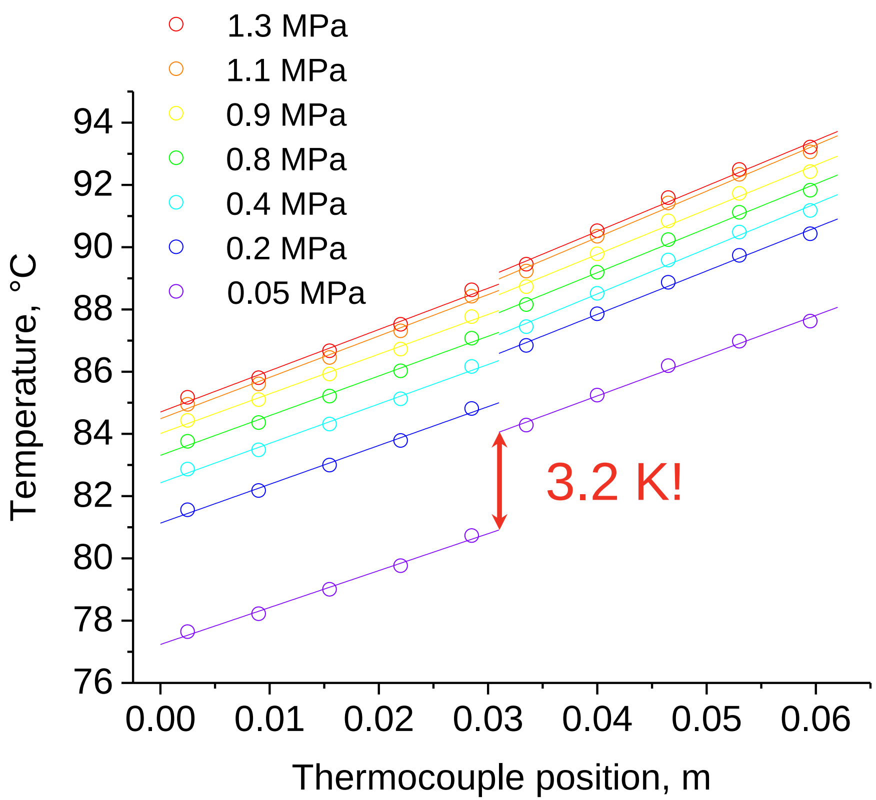


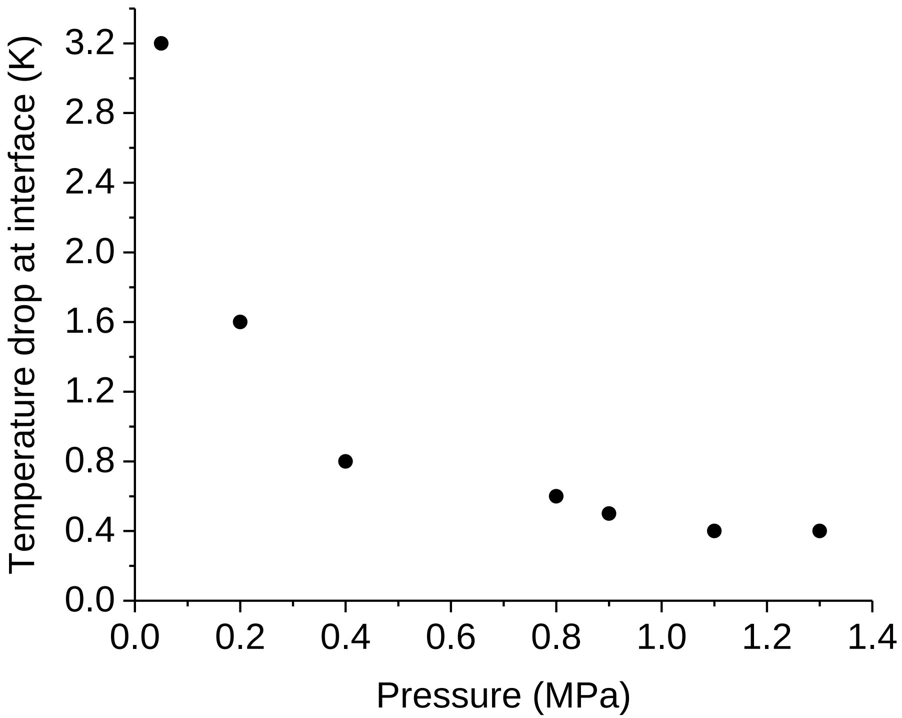
10 thermocouples @ reference bars

Thermal contact resistance vs Pressure applied

No specimen, just the interface between the reference bars!

Interface material: 70 um graphite sheets

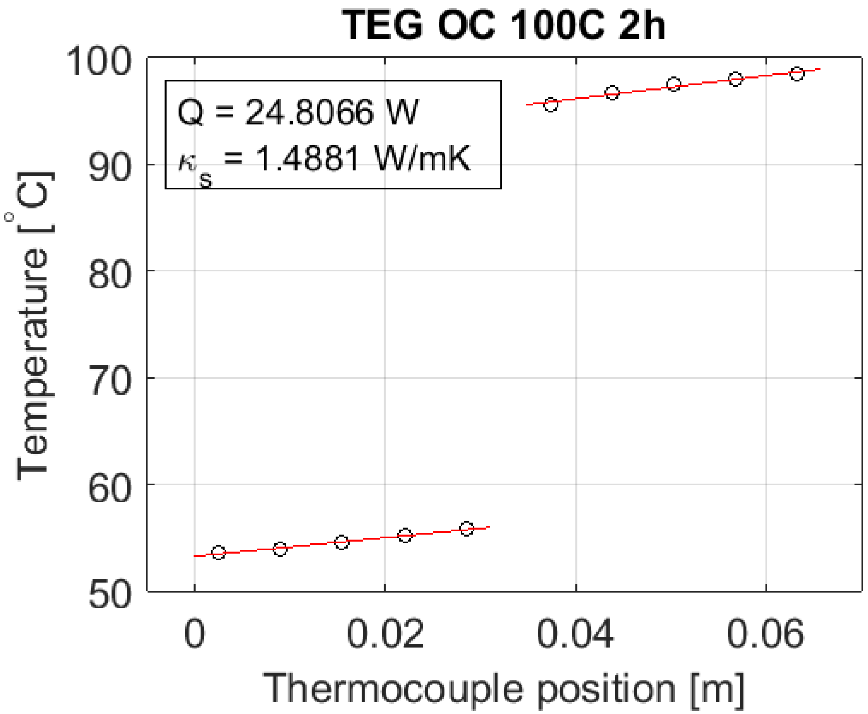




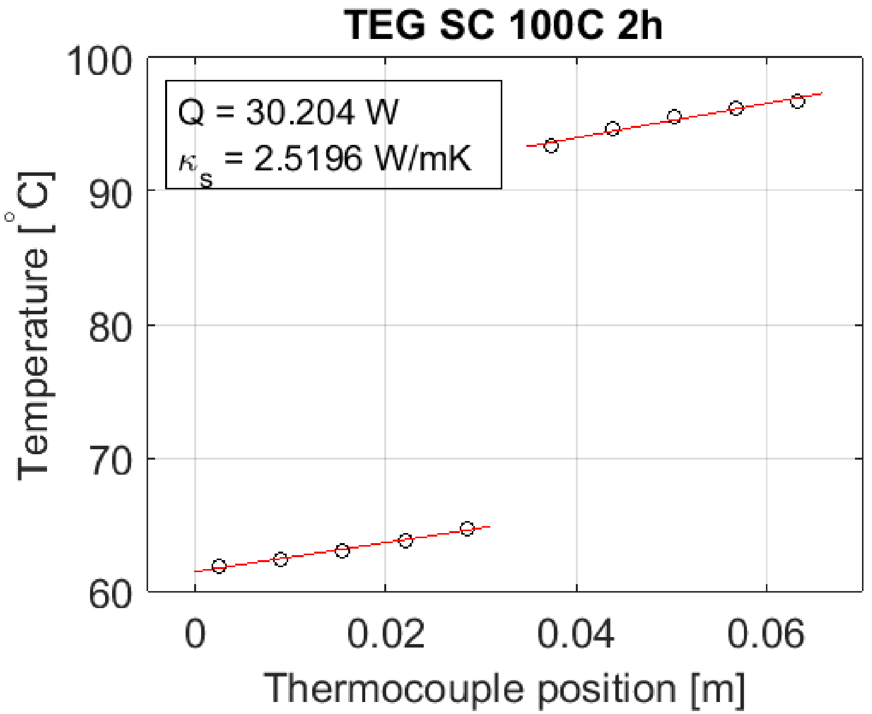
Thermal conductivity of TE module

Change of heat flux depending on the operating mode:

Open circuit



Short circuit



Conclusions

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- Measurement of κ is very challenging
- Trade-off between:
  - High accuracy = complex setup calibrated for unique sample κ and geometry
  - High reproducibility – less complex, practical solution applicable for industry and academia. Uncertainty ~ 15%

Thank you for your attention!

SolCell Metrology for MJSC

European Metrology Research Programme (EMRP)