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Uncertainty Workshop: Overview of uncertainty factors in HTGHPs

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Final Stakeholder Meeting

NPL, Teddington, United Kingdom

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DIN/EU Standards for GHPs

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- **ISO 8302:1991** Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus
- **EN 1946-2:1999** Thermal performance of building products and components - Specific criteria for the assessment of laboratories measuring heat transfer properties - Part 2: Measurements by the guarded hot plate method
- **EN 12664:2001** Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Dry and moist products with medium and low thermal resistance
- **EN 12667:2001** Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance
- **EN 12939:2001** Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Thick products of high and medium thermal resistance
- **CEN/TS 15548-1:2014** Thermal insulation products for building equipment and industrial installations - Determination of thermal resistance by means of the guarded hot plate method - Part 1: Measurements at elevated temperatures from 100 °C to 850 °C

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Guarded Hot-Plate apparatus

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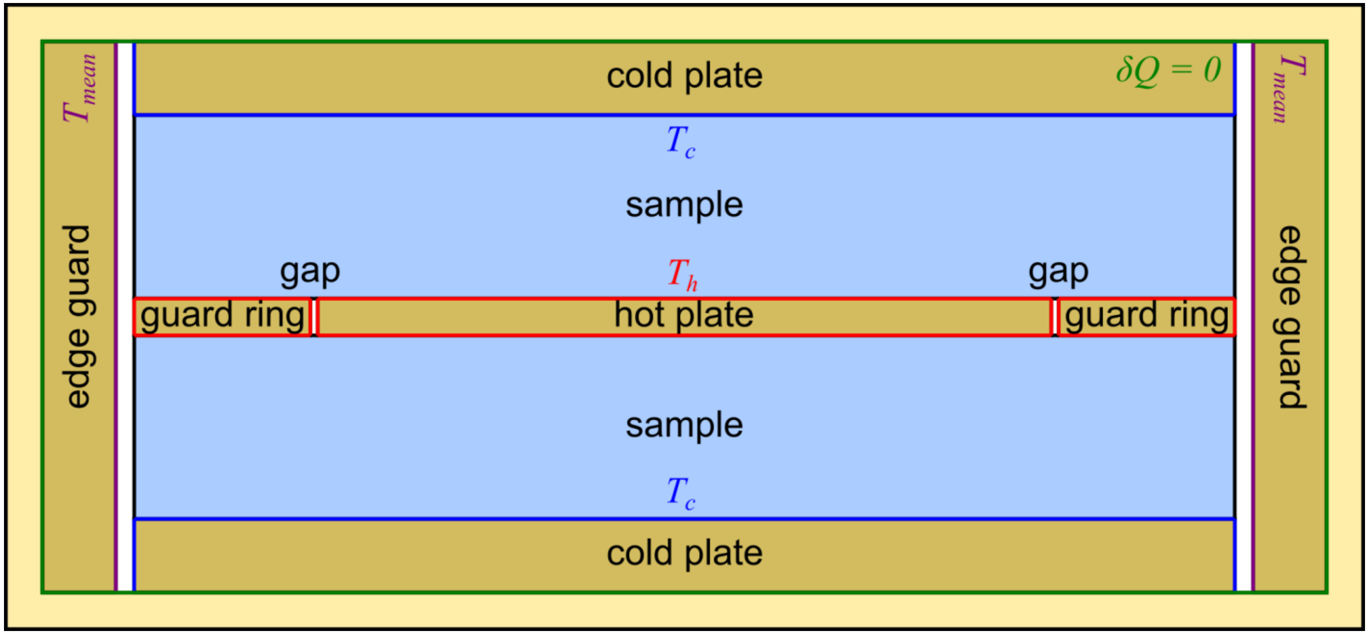

Working equation for two-specimen apparatus:

$$\lambda(T_m) = \frac{\Phi \cdot d}{2 \cdot A \cdot (T_h - T_c)} \quad \text{with} \quad T_m = (T_h + T_c)/2$$

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Uncertainty assessment

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- According to the *Guide to the Expression of uncertainty in Measurement* (GUM)

- **Ideal model**: $$\lambda(T_m) = \frac{\Phi \cdot d}{2 \cdot A \cdot (T_h - T_c)}$$

- Combined standard uncertainty of heat conductivity $\lambda(x) = \lambda(\Phi, d, A, T_h, T_c)$:

$$u_c(\lambda) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial \lambda(x)}{\partial x_i} \right)^2 u^2(x_i)}$$

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Real model, e.g., HTGHP LNE1

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$$\lambda(T_m) = \frac{\Phi}{A \cdot \left[\frac{(T_{HP,1} - T_{CP,1})}{d_1} + \frac{(T_{HP,2} - T_{CP,2})}{d_2} \right]} + \Delta\lambda_{HP-GR-imbalance} + \Delta\lambda_{S-EG-imbalance} + \Delta\lambda_{TCR}$$

$$T_m = \frac{T_{HP,1} + T_{CP,1} + T_{HP,2} + T_{CP,2}}{4}$$

$$\Phi = \alpha_{junct} \cdot \frac{U_{heat} \cdot U_{res}}{R_{res}(T_{res})}$$

$$A = [1 + \alpha_{HP} \cdot (T_{HP} - T_0)]^2 \cdot \frac{[l_{HP}^2(T_0) + l_{GR}^2(T_0)]}{2}$$

$$d = d_0 \cdot [1 + \alpha_d \cdot (T_m - T_0)]$$

α_{junct} : power dissipation of junctions

U_{heat} : voltage of heating wire

U_{res} : voltage of standard resistor

R_{res} : resistance of standard resistor

α_{HP} : thermal expansion coefficient of hot plate

l_{HP} : length of hot plate

l_{GR} : inner length of guard ring

α_d : thermal expansion coefficient of sample

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Uncertainty sources

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1) **Equipment related uncertainties:**
   a) Specimen thickness
   b) Metering area
   c) Temperature difference across specimen
   d) Input power of the hot plate
   e) Miscellaneous uncertainty sources

2) **Specimen related uncertainties:**
   a) Absolute mean temperature
   b) Miscellaneous uncertainty sources

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1a) Specimen thickness

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Measurement at room temperature outside GHP (with e.g. calliper, straight edge, feeler gauge):

- Calibration of instrument(s)
- Resolution of instrument(s)
- Drift of instrument(s)

In-situ measurement inside GHP with laser displacement sensor:

- Calibration of instrument
- Resolution of instrument
- Fitting error of the calibration of laser displacement error
- Drift of instrument
- Influence of ambient conditions on instrument
- Thermal expansion of GHP (e.g., plates)

Reproducibility of thickness measurement

Variation in sample thickness

Effect of pressure applied to the sample

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1a) Specimen thickness

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Corrections for thermal expansion:
Thermal expansion coefficient
Mean sample temperature (T_0, T)
Thermal expansion of spacer blocks (for compressible materials)
Effect of pressure applied to the sample (for compressible materials)
Variation of thickness with pressure (for compressible materials)
Miscellaneous uncertainty factors:
Operator effect (including vertical misalignment; variation in reading from different operators, noises on results)
Temperature effect
Effect of pressure load for double specimen GHP

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1b) Metering area

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Dimension measurement at room temperature (diameter of hot plate, inner diameter of guard ring):
Calibration of calliper
Resolution of calliper
Drift of calliper
Operator effect (including misalignment, repeatability of the measurement)
Corrections for thermal expansion:
Thermal expansion coefficient of hot plate
Thermal expansion coefficient of guard ring
Mean temperature of hot plate (T_0, T)
Mean temperature of guard ring (T_0, T)

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1c) Temperature drop across specimen

Uncertainties of digital voltmeter (dvm):
Calibration of dvm
Resolution of dvm
Drift of dvm
Uncertainties of thermocouples (tcs):
Calibration of tcs:
Calibration of the standard temperature sensor
Drift of the standard temperature sensor
Isothermal conditions when calibrating sensors
Noises on results of calibration
Electrical connections (parasitical emf)
Cold junction temperature
Response model used for each sensor

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1c) Temperature drop across specimen

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Uncertainties of thermocouples (tcs):
Interpolation error of tcs
Spread of tcs from fitting curves (differences between tcs)
Drift of each sensor
Noise of each temperature result (repeatability)
Temperature stability (variation with time)
Parasitic voltages (connections, switches)
Homogeneity of tc (along the sensor)
Heat conduction of tc stem
Installation, position of tcs
Homogeneity:
Temperature spread across metering area
Temperature spread across the heated cold plate

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1d) Input power of the hot plate

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Uncertainties of voltage measurement with digital voltmeter (dvm):
Calibration of dvm
Resolution of dvm
Drift of dvm
Repeatability, noises
Corrections due to conditions differing from those of calibration
Electrical connections
Uncertainties of current measurement with digital voltmeter (dvm):
Calibration of dvm
Resolution of dvm
Drift of dvm
Repeatability, noises
Corrections due to conditions differing from those of calibration
Electrical connections

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1d) Input power of the hot plate

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Uncertainties of resistor measurement:
Calibration of standard (shunt) resistor
Drift of shunt resistor
Corrections due to conditions differing from those of calibration
Uncertainties due to resistance of cold ends (for cable heaters):
Length of wire in metering area
Total length of heater wire
Resistance of heating element/wires
Effect of electrical resistance between metering heater and lateral guard heater
Impedance of electrical insulation (for high T)
Stability of power source

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1e) Miscellaneous uncertainties

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Lateral heat flow across gap between main heater and guard ring due to temperature imbalance (centre-guard imbalance)
Edge heat losses at gap between main heater and guard ring (influence of gap content)
Heat transfer (conduction, convection, radiation) at lateral edges of specimen at transition to gap and/or edge guard
For single-specimen GHPs: heat transfer between metering and auxiliary area
Deviation from steady state conditions (thermal equilibrium)
Flatness of heater plates
Emissivity of heater plates
Repeatability, reproducibility of thermal conductivity measurement (dispersion of results)

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2) Specimen related uncertainties

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a) Absolute mean temperature:
Calibration of tcs
Spread of tcs from fitting curves
Resolution of dvm
Calibration uncertainty of the PRT
Calibration of dvm
Interpolation error of tcs

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2) Specimen related uncertainties

b) Miscellaneous uncertainty sources:
For porous samples: effective thermal conductivity = thermal conductivity of solid material, gas-filled pores → temperature-dependent thermal conductivity
For porous, (semi-)transparent samples: effective thermal conductivity = thermal conductivity of solid material, gas-filled pores, radiation → temperature-dependent thermal conductivity
Inhomogeneity of specimen
For two-specimen GHPs: Non-identical specimens
Thermal contact resistance between specimen and plates
Thermal contact resistance between specimen and thermocouples

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Example: HTGHP LNE1, HDCaSi

Uncertainty source	Percentage of overall uncertainty at 650 °C	Percentage of overall uncertainty at 150 °C
Metering area	1	1
Thickness of specimens	1	1
Repeatability, reproducibility	4	5
Power supplied to metering heater	6	5
Thermal contact resistance	8	19
Temperature imbalance between specimen and edge guard	14	7
Temperature difference across specimens	24	12
Temperature imbalance between metering heater and guard ring	41	49

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Example: HTGHP LNE1, HDCaSi

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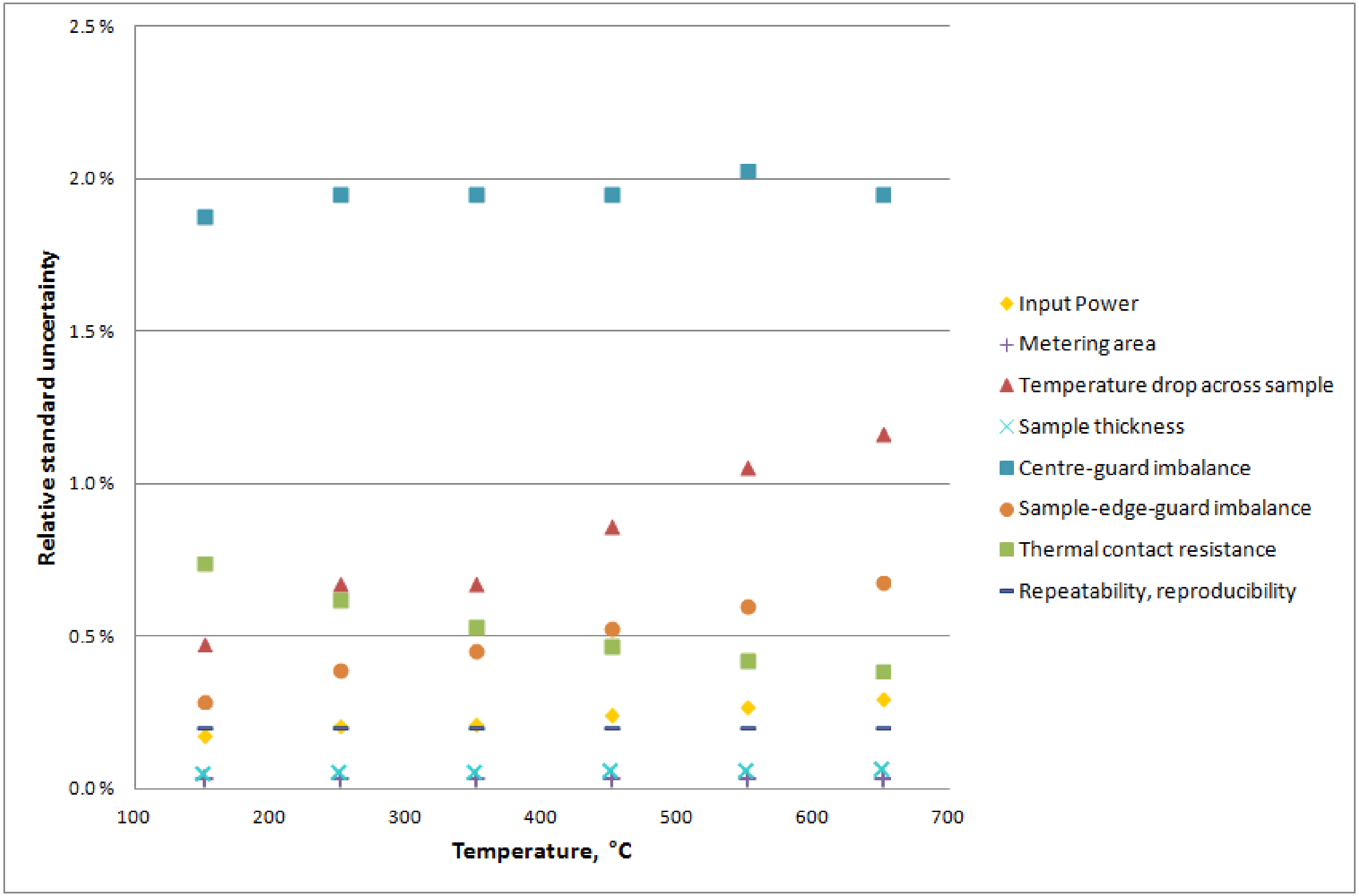

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Conclusions

- Uncertainties with lowest influence:
  - Specimen thickness
  - Metering area
- Most prominent uncertainty:
  - Temperature imbalance between metering heater and guard ring
- Increasing uncertainties with increasing temperature:
  - Temperature drop across specimen
  - Temperature imbalance between specimen and edge guard
  - Input power of metering heater
- Decreasing uncertainty with increasing temperature:
  - Thermal contact resistance

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