

1 **Supplementary data:**

2 **Improving the comparability of FFF-3D printing emission data by adjustment of the set extruder**
3 **temperature**

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8

9 This document includes additional figures and an estimation of the measurement uncertainty of the
10 temperature measurement.

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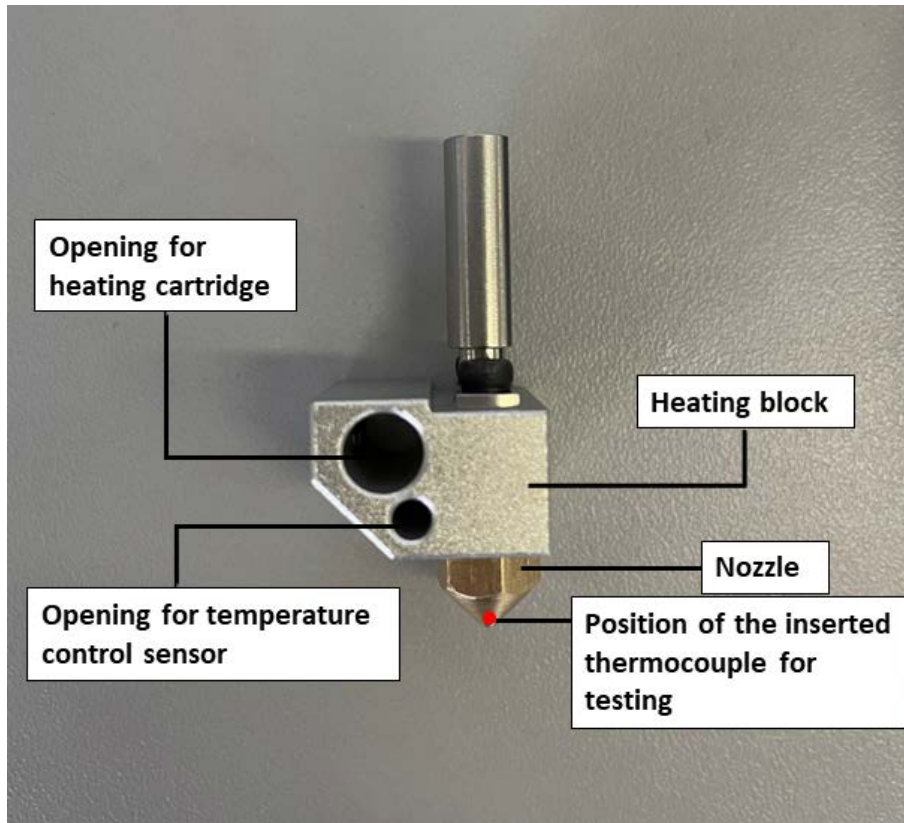
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42 **Figures**

43 *Figure S1: Positions of the heating cartridge, the temperature control sensor and the nozzle in a heating block. Position of the*
44 *thermocouple for temperature testing is marked with a red dot.*



45

46

47 AnyM uses a “Bowden extruder type”, i.e., the stepper motor and the hotend are located separately. It
48 extruded significantly below the set value in the G Code. Therefore, the extrusion value was empirically
49 increased in order to fulfill the target of 800 mm filament extrusion for SPM (see Figure S2). Further
50 explanation can be found below.

51 *Figure S2: Example SPM G Code for AnyM*

```
M104 SX                ;set Extruder temperature X (no wait)
M190 SY                ;set Printing bed temperature Y (wait)
M109 SX                ;set Extruder temperature X (wait)
G21                    ; mm
G90                    ; abs
G92 E0                 ; reset extruder
G28 X0 Y0 Z0
G1 X93 Y92 F3600
G1 Z180
G92 E0
G1 F17 E108.5 Z155
G92 E0
G1 F17 E108.5 Z180
G92 E0
G1 F17 E108.5 Z155
G92 E0
G1 F17 E108.5 Z180
G92 E0
G1 F17 E108.5 Z155
G92 E0
G1 F17 E108.5 Z180
G92 E0
G1 F17 E108.5 Z155
G92 E0
G1 F17 E108.5 Z180
G92 E0
G28 X0 Y0
M104 S0                ;turn off extruder heater
M140 S0                ;turn off bed heater
M107
M84
```

52

53 *Figure S3: Example SPM G Code for CP*

```

M104 SX           ;set Extruder temperature X
M190 SY           ;set Printing bed temperature Y
M109 SX           ;set Extruder temperature X
G21               ;metric values
G90               ;absolute positioning
M82               ;set extruder to absolute mode
M107              ;start with the fan off
M117              Printing...
G28 X0 Y0 Z0
G1 X80 Y80 F3600
G1 Z180
G92 E0
G1 F68 E800       ;extrude 800mm at 68 mm per min
G92 E0
G28 X0 Y0
M104 S0           ;extruder heater off
M140 S0           ;heated bed heater off (if you have
it)
M6013 S0          ;chamber temperature set to zero.
M84 X Y E         ;steppers off
G90               ;absolute positioning
M117              Print finished.

```

54

55 *Figure S4: Example SPM G Code for CB2*

```

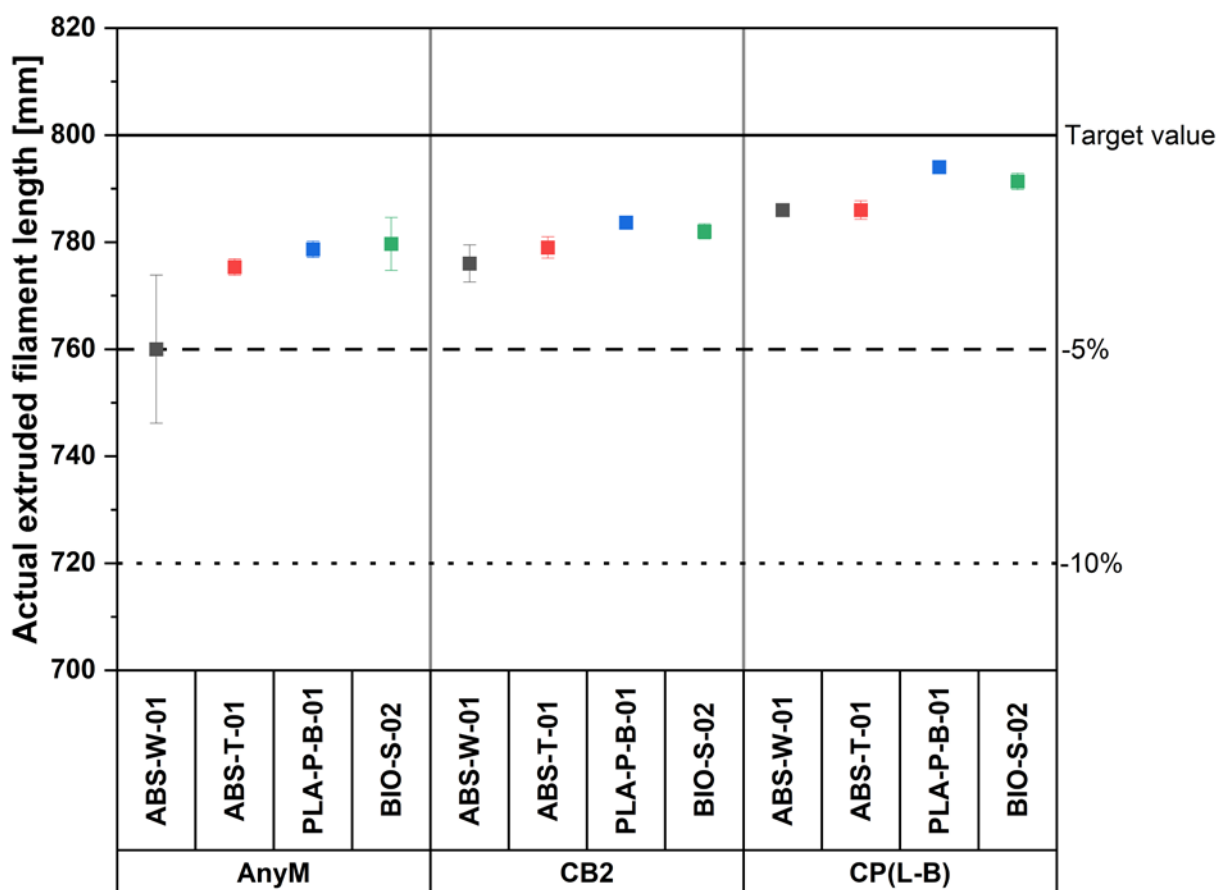
G28 X0 Y0
G28 Z0
M104 SX           ;set Extruder temperature X (no wait)
M190 SX           ;set Printing bed temperature Y (wait)
M109 SX           ;set Extruder temperature X (wait)
G21               ; mm
G90               ; abs
G92 E0            ; reset extruder
G1 X120 Y110 F3600
G1 Z180
G92 E0
G1 F30 E200 Z130
G92 E0
G1 F30 E200 Z180
G92 E0
G1 F30 E200 Z130
G92 E0
G1 F30 E200 Z180
G92 E0
G28 X0 Y0
G28 Z0
M104 S0           ;turn off extruder heater
M140 S0           ;turn off bed heater
M107
M84

```

56

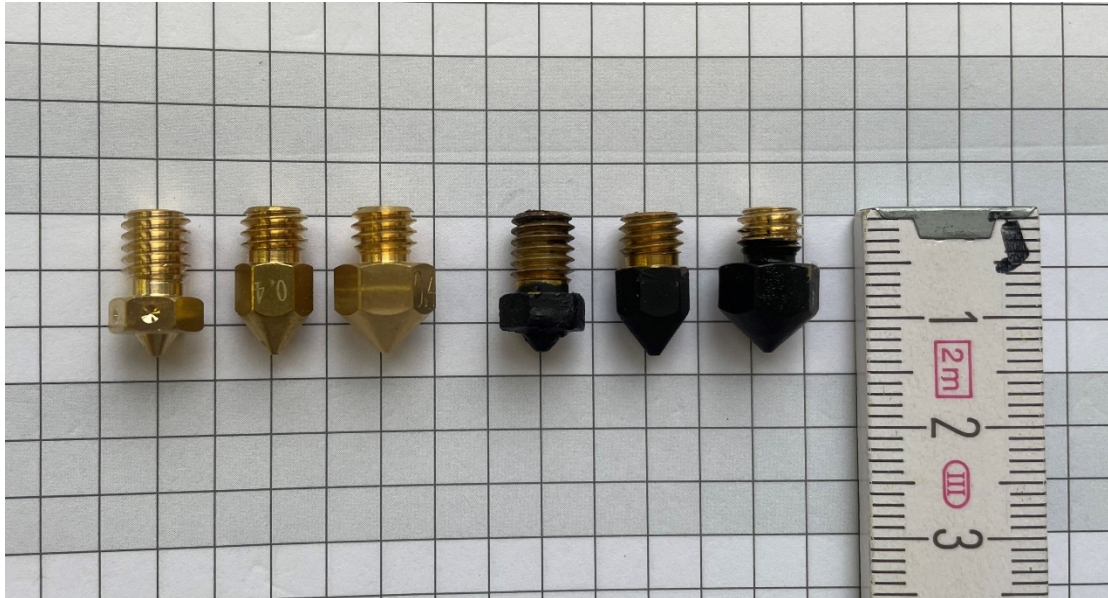
57 The reproducibility of SPM on different printer models was examined by measuring the actual extruded
 58 filament length. The extrusion value was set to 800 mm in the G Code with the aim to extrude a maximum
 59 filament length of 800 mm. In practice, the actual extruded filament length is usually slightly below the set
 60 extrusion value due to factors like the extruder type, the extruder temperature, as well as the rheological
 61 properties of the filament material. The printers CB2 and CP(L-B) showed only minor deviations (<4 %) to
 62 the target value. AnyM, however, had initially significant deviations for some tested filaments of above
 63 10 %. Therefore, the G Code of AnyM was modified (see Figure S2) in order to compensate its original
 64 offset. Overall, the developed G Codes enabled a reproducible extrusion process with an average of
 65 maximum 5 % deviation from the target value. The extrusion duration was constant at 11.75 min (AnyM),
 66 11.78 min (CB2) and 11.83 min (CP).

67 *Figure S5: Reproducibility of SPM on different printer models*



68

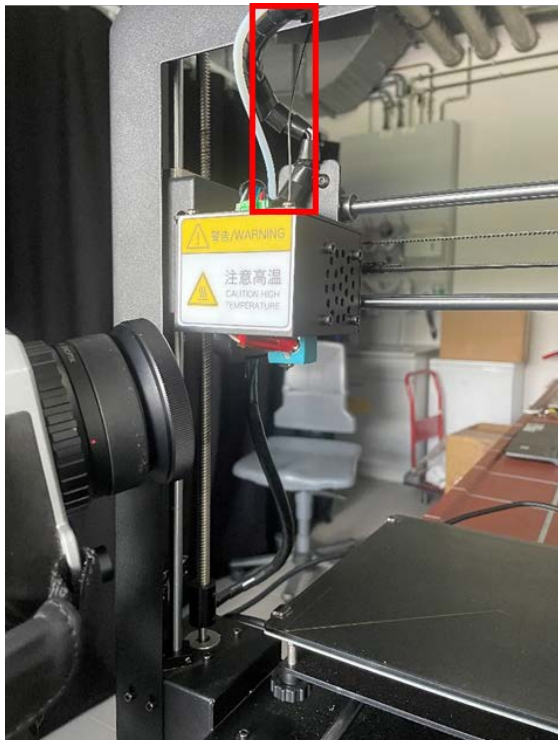
69 *Figure S6: Brass nozzles with and without paint. AnyM (left), CP (middle), CB2 (right)*



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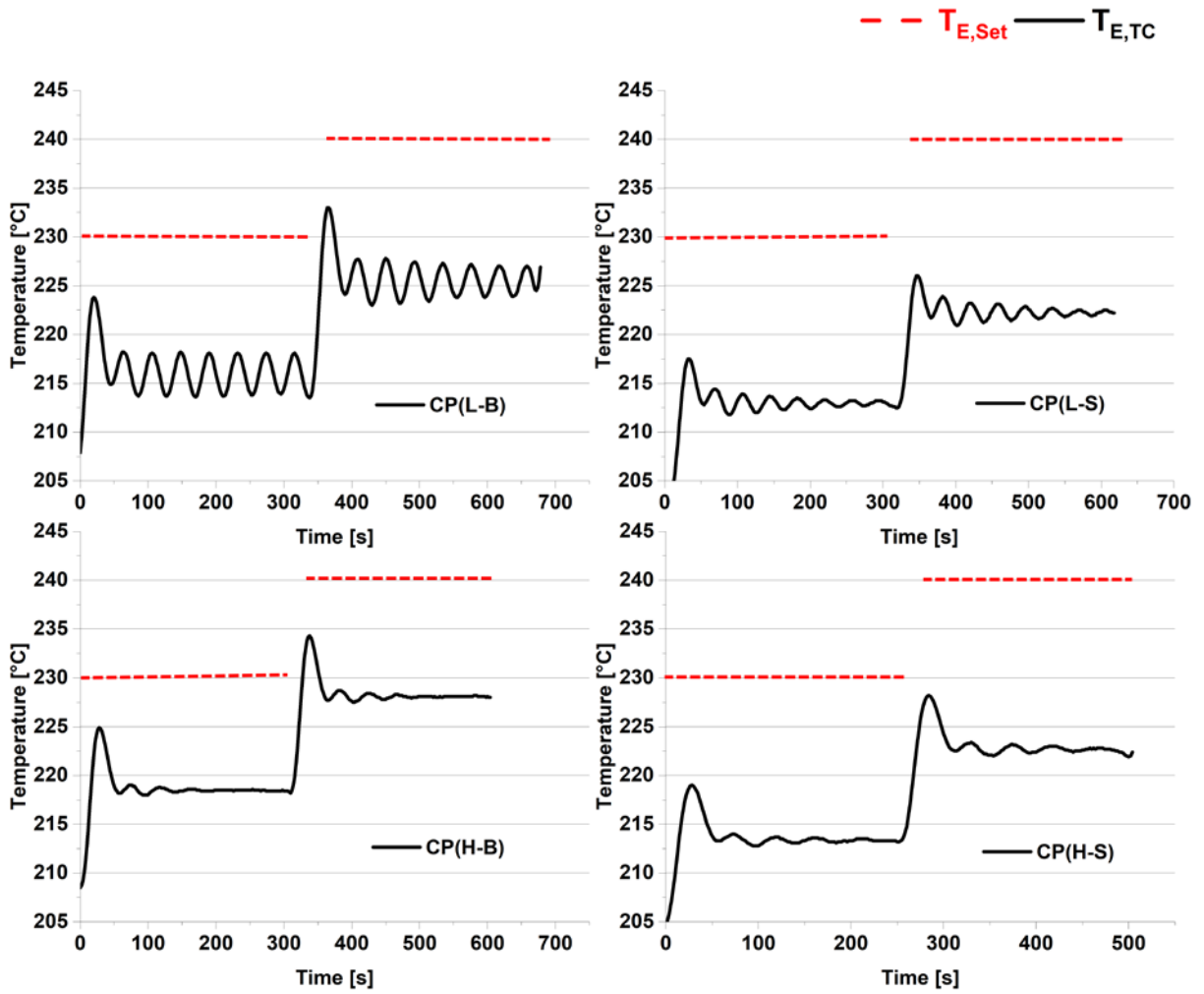
72 *Figure S7: Nozzle temperature measurement with thermocouple (marked) and infrared camera on AnyM*



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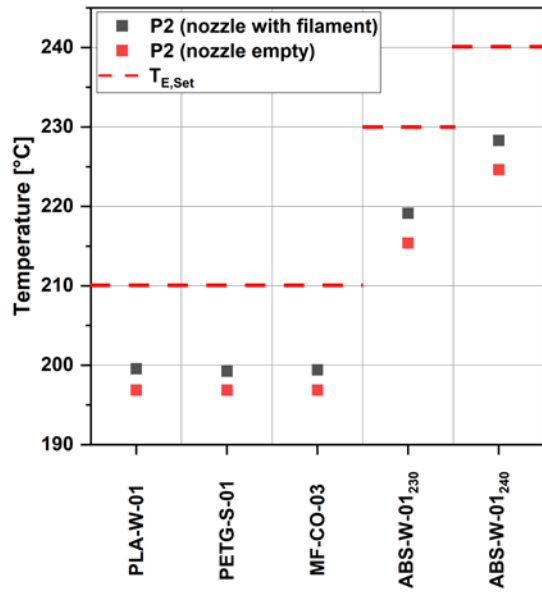
74

75 Figure S8: Temperature over time at unadjusted set temperatures 230°C and 240°C for four hotend and nozzle combinations in
 76 printer CP measured with the thermocouple. L: Low temperature hotend, H: High temperature hotend, B: Brass nozzle, S: Hardend
 77 steel nozzle



78

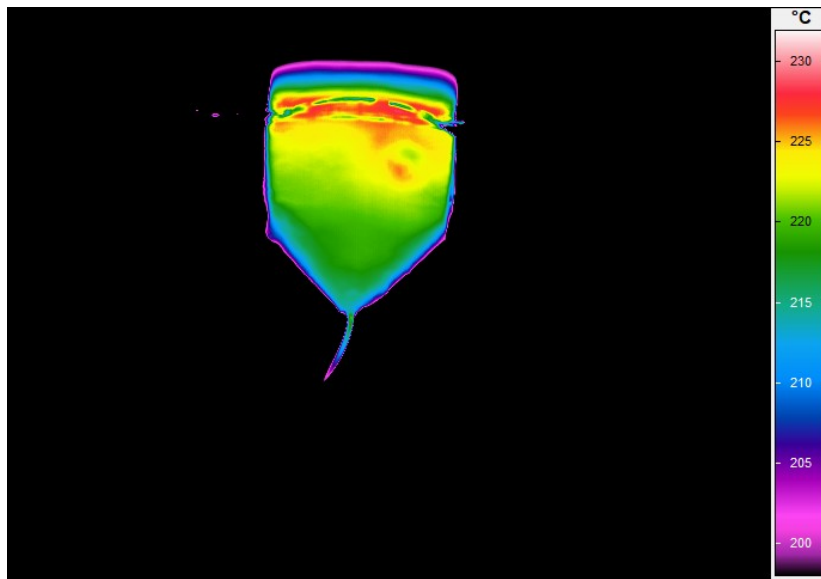
79 Figure S9: IR measurement-based temperatures of the nozzle surface (with and without filament extrusion) for a selection of
80 filaments tested on CB2. The filament ABS-W-01 was evaluated at 230 °C and 240 °C set temperature.



81

82

83 Figure S10: Thermogram of CB2 during extrusion of ABS-W-01, set temperature at 230°C

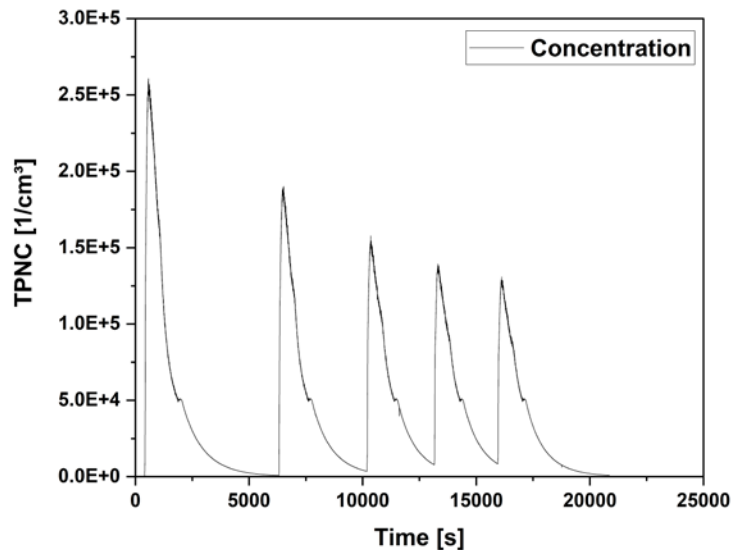


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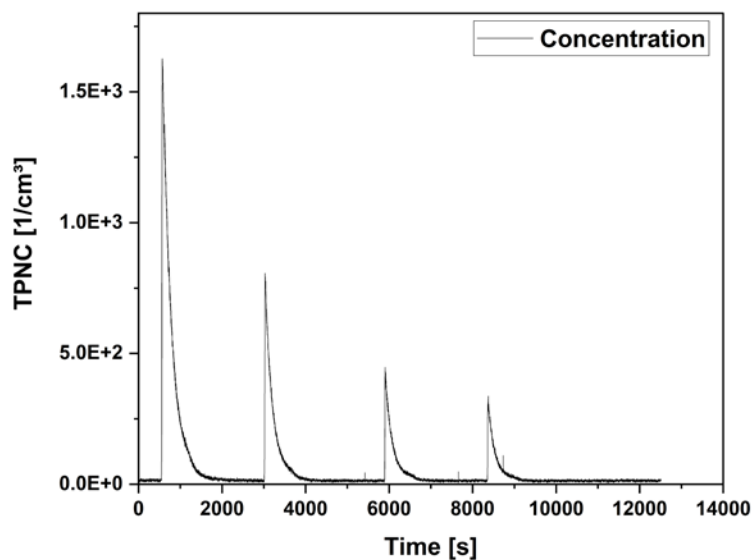
86 Figure S11 shows the printer blank emission of AnyM with heat block coating. It was observed that the
87 TPNC declined with each subsequent print job on the same day but remained at a high level. The TPNC fell
88 back to its initial level on the next day.

89 *Figure S11: AnyM printer blank with coating at $T_{E,Set}=230^{\circ}\text{C}$ and $T_B=80^{\circ}\text{C}$. Five consecutive heating cycles are shown.*



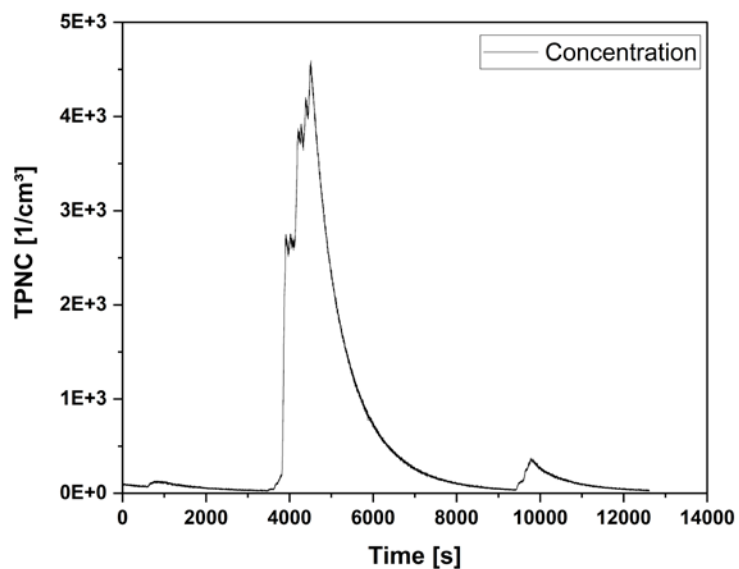
90
91 After removing the heat block coating, the printer blank emission decreased substantially to a negligible
92 level (see Figure S12).

93 *Figure S12: AnyM printer blank without coating at $T_{E,Set}=230^{\circ}\text{C}$ and $T_B=80^{\circ}\text{C}$. Four consecutive heating cycles are shown.*



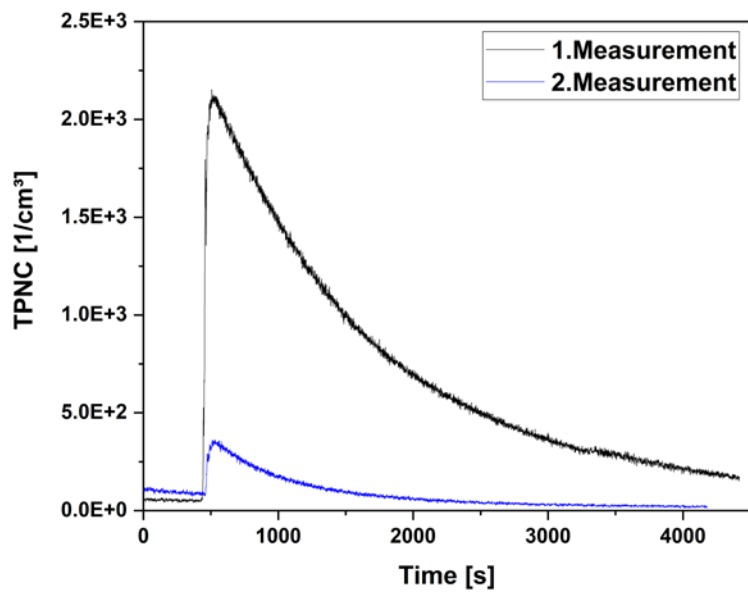
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96 *Figure S13: CB2 printer blank at $T_{E,Set}=240^{\circ}\text{C}$ and $T_B=110^{\circ}\text{C}$. Two consecutive heating cycles are shown.*



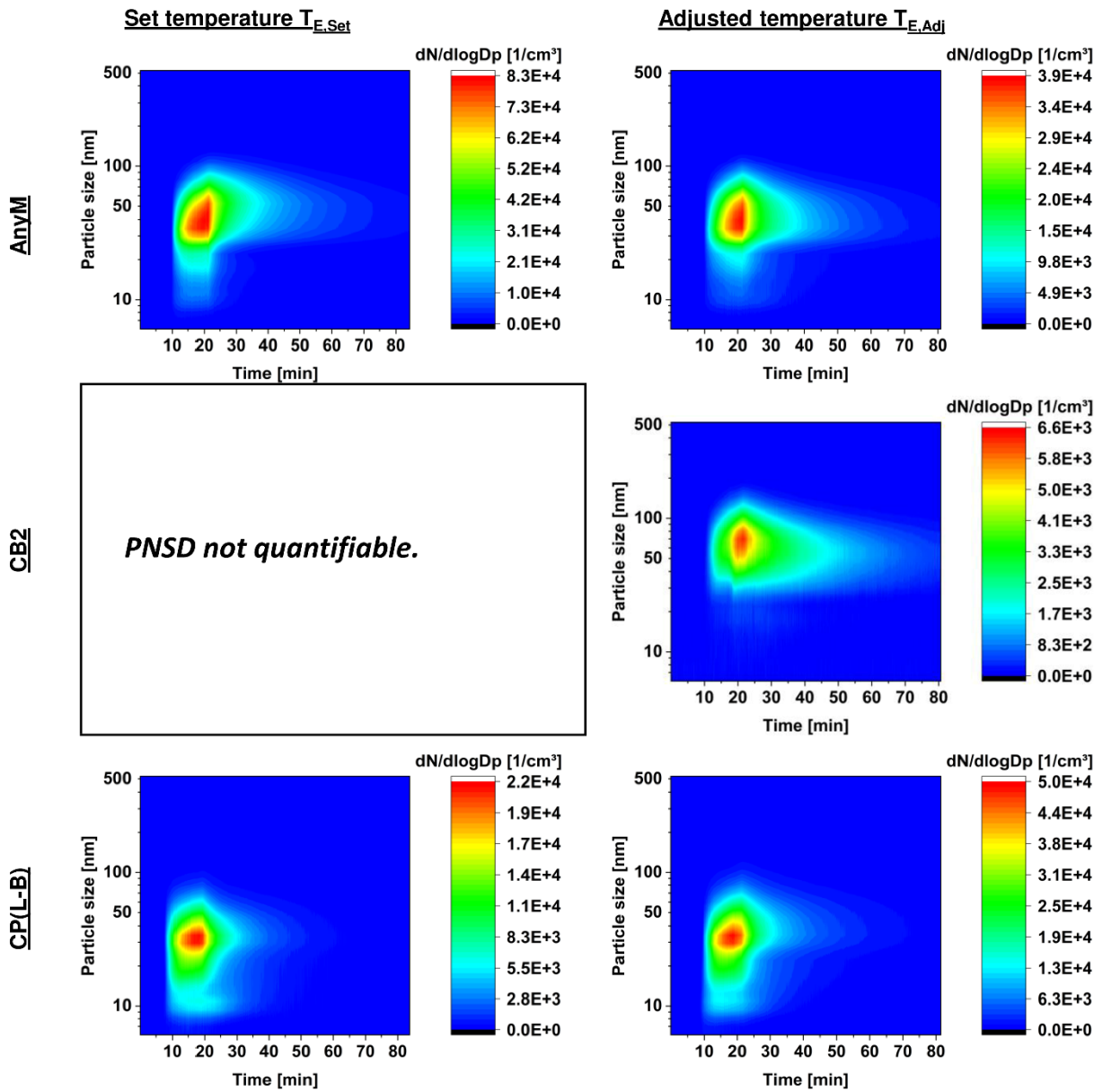
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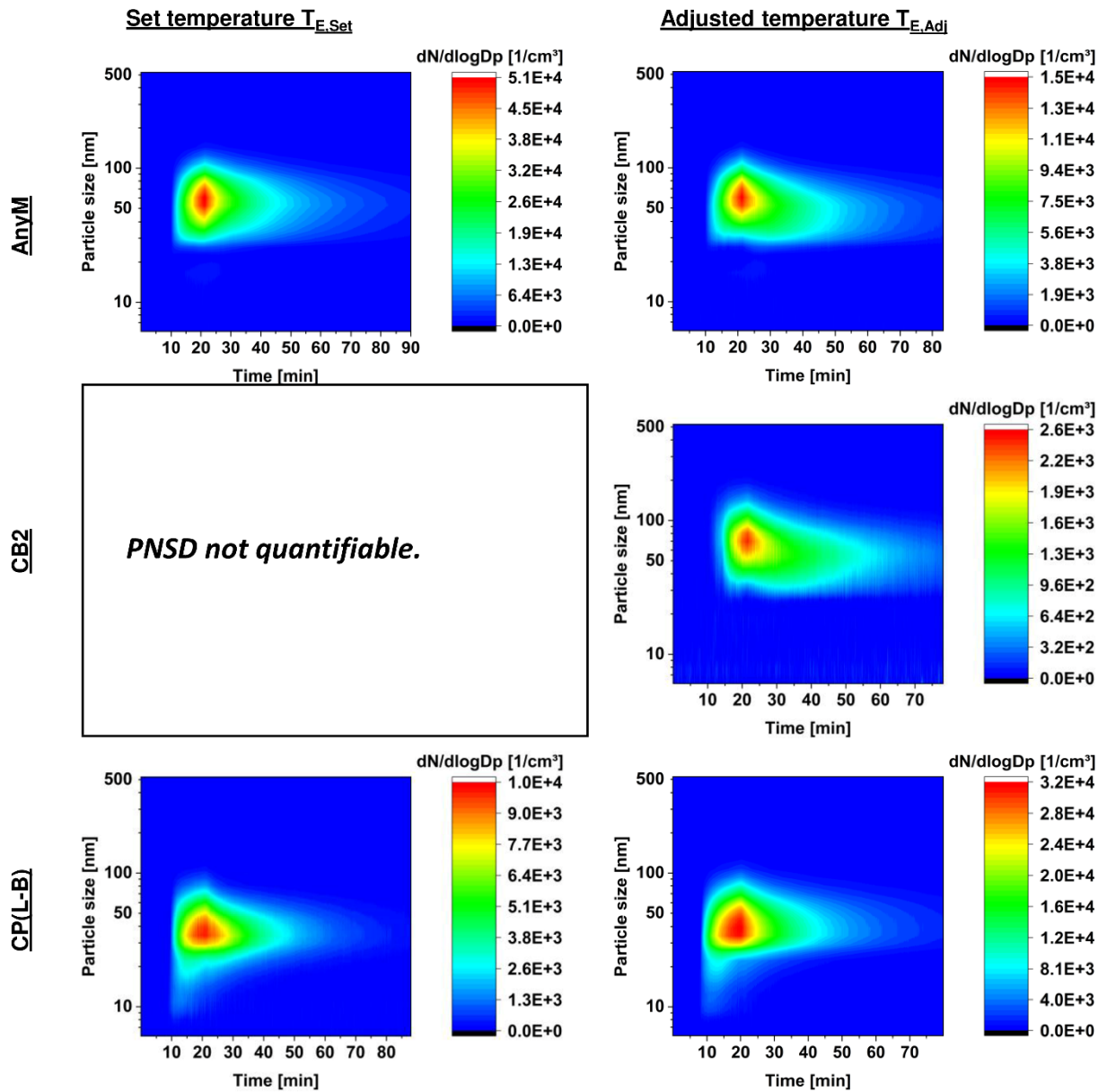
98 *Figure S14: CP(L-B) printer blank at $T_{E,Set}=245^{\circ}\text{C}$ and $T_B=110^{\circ}\text{C}$. Two consecutive heating cycles are shown.*

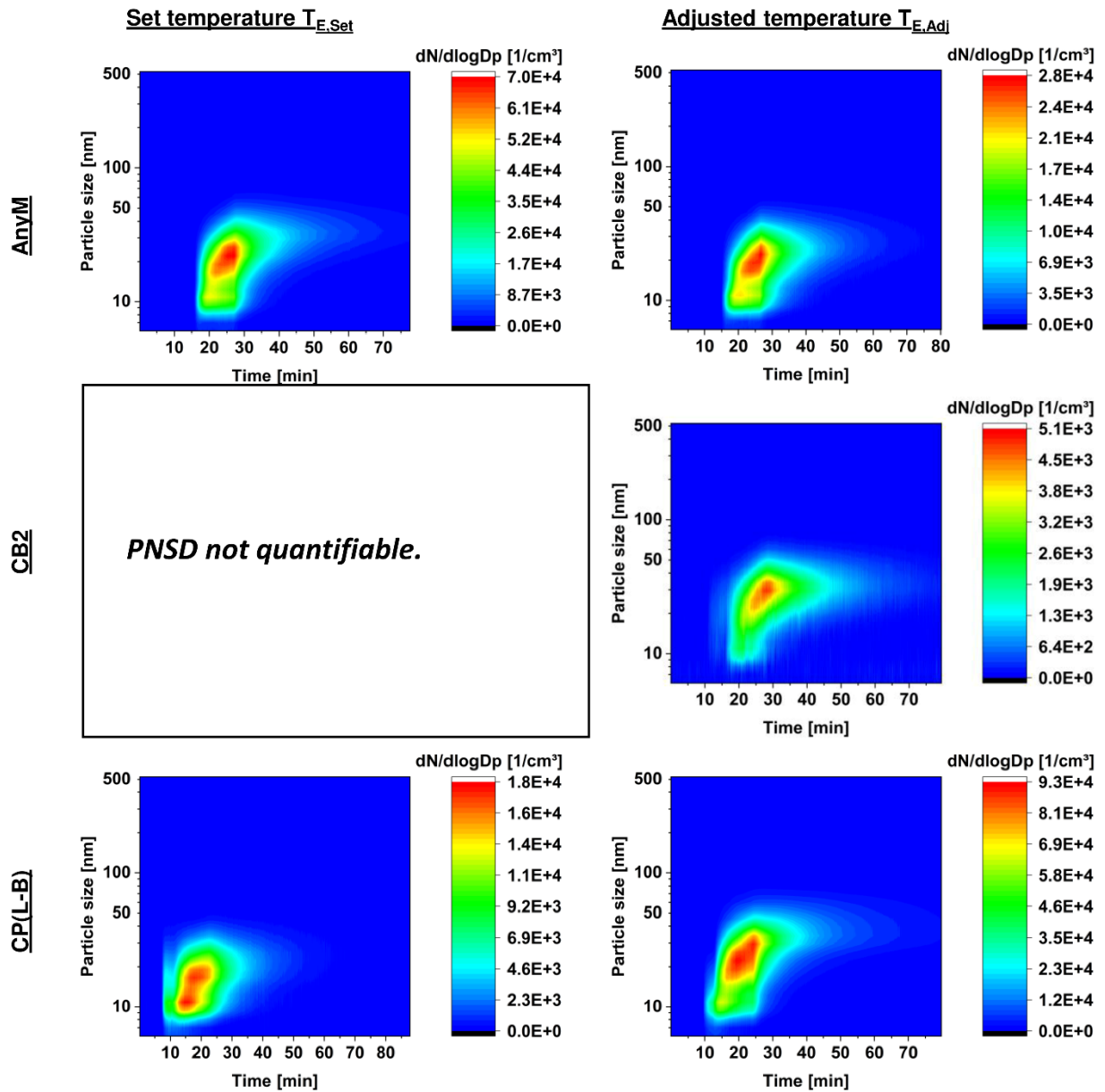


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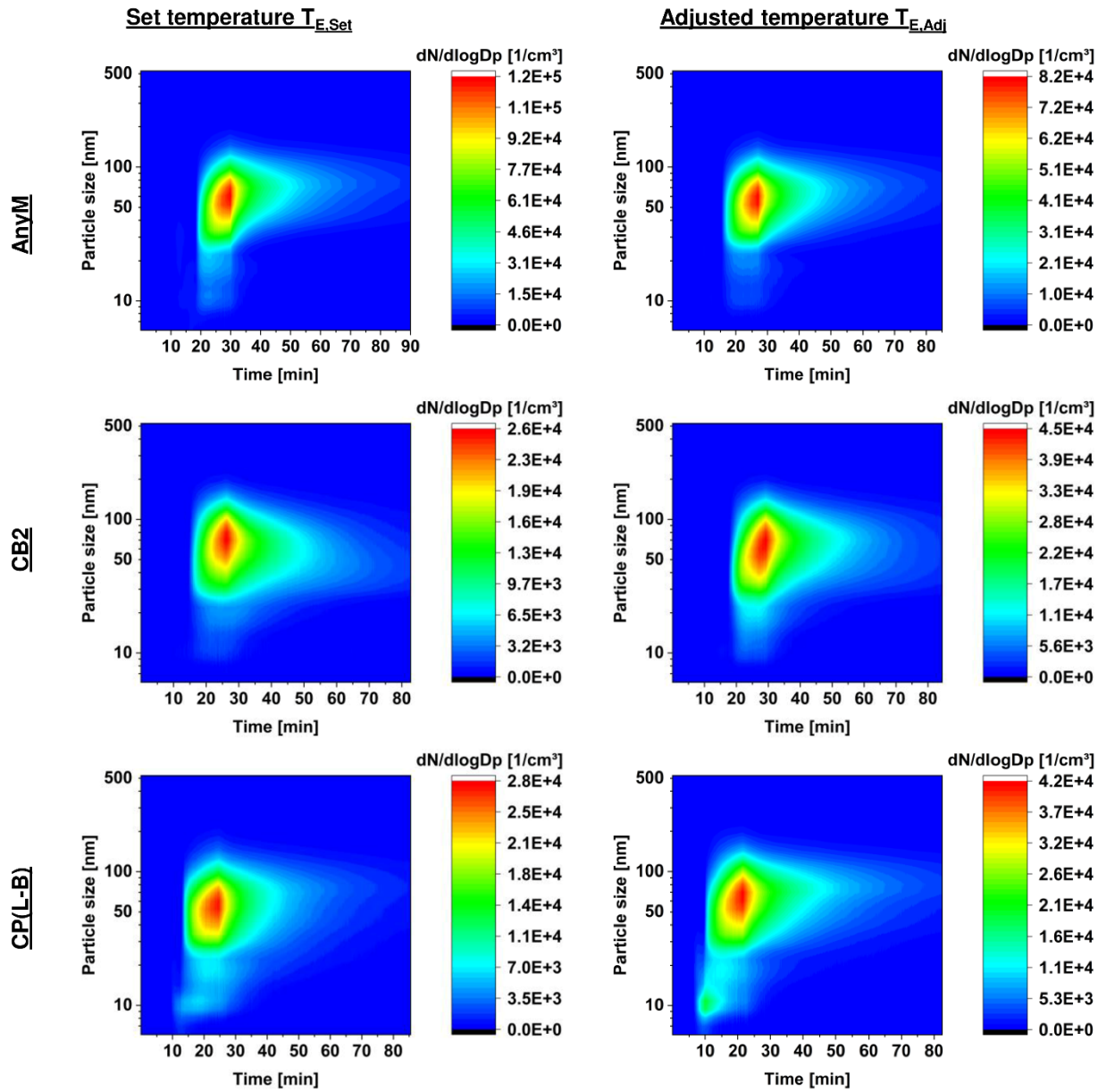






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111 Measurement uncertainty of the temperature measurement

112 Estimation of the measurement uncertainty of IR thermography

113 Type B evaluation of standard uncertainty according to ISO/IEC Guide 98-3:2008 ¹

114 The measurement uncertainty in thermography consists of:

- 115 1. The measurement uncertainty of the adjustment/calibration of the infrared camera
116 $a(T_{cal}) = \pm 1.5 \text{ K}$ and $a(T_{cal}) = \pm 0.015 \cdot T$; for $T > 100 \text{ }^\circ\text{C}$
117 Examples are given for the respective interval limit of the printer's operating temperature
118 ranges. However, the maximum real extruder temperature is $385 \text{ }^\circ\text{C}$ for CP(H-S). Therefore,
119 example calculations are given for $180 \text{ }^\circ\text{C}$, $260 \text{ }^\circ\text{C}$ and $385 \text{ }^\circ\text{C}$:

120
121 $a(180) = \pm 0.015 \cdot 180 = \pm 2.70 \text{ K}$

122 $a(260) = \pm 0.015 \cdot 260 = \pm 3.90 \text{ K}$

123 $a(385) = \pm 0.015 \cdot 385 = \pm 5.78 \text{ K}$

124

- 125 2. The measurement uncertainty of the paint emissivity ϵ

126 $a(\epsilon) = \pm 0.02$

127

- 128 3. Other aspects, e.g., measurement distance or environmental conditions (ambient air
129 temperature, air humidity, etc.) may also influence.

130 The measurements were carried out in a climatic room ($T=23 \text{ }^\circ\text{C} \pm 2 \text{ K}$, $\text{RH}= 42 \% \pm 7 \%$). The climatic
131 condition and measurement distance were considered in the camera software. For the sake of simplicity,
132 only the given uncertainties of the camera calibration and of the emissivity parameter are considered in
133 this estimation.

134 The respective standard uncertainty can be calculated by assuming a symmetric rectangular distribution:

135
136 1. $u(T_{cal}) = \frac{a(T_{cal})}{\sqrt{3}}$ (1)

135

136 Examples:

137 $u(180) = \frac{2.70 \text{ K}}{\sqrt{3}} = 1.56 \text{ K}$; $u(260) = \frac{3.90 \text{ K}}{\sqrt{3}} = 2.25 \text{ K}$; $u(385) = \frac{5.78 \text{ K}}{\sqrt{3}} = 3.33 \text{ K}$

138 2. $u(\epsilon) = \frac{a(\epsilon)}{\sqrt{3}}$ (2)

138 $u(0.02) = \frac{0.02}{\sqrt{3}} = 0.012$

139 The following factors contribute to the measurement uncertainty:

140 1. $u_{cal}(T) = u(T_{cal})$ (3)

141 2. $u_\epsilon(T) = |c_\epsilon|u(\epsilon) \approx |Z_\epsilon| = \left| \frac{1}{2} \{f[\epsilon + u(\epsilon)] - f[\epsilon - u(\epsilon)]\} \right| = \left| \frac{1}{2} \left\{ f \left[\epsilon + \frac{a(\epsilon)}{\sqrt{3}} \right] - f \left[\epsilon - \frac{a(\epsilon)}{\sqrt{3}} \right] \right\} \right|$ (4)

140 Examples for the paint emissivity of $\epsilon = 0.93 \pm 0.02$ and $T= 180 \text{ }^\circ\text{C}$, $260 \text{ }^\circ\text{C}$ and $385 \text{ }^\circ\text{C}$ are given. The
141 temperature change due to a change in ϵ of $+u(\epsilon)$ and of $-u(\epsilon)$ was considered.

142

$$143 \quad u_{\epsilon}(180) = \left| \frac{1}{2} \left\{ f \left[0.93 + \frac{0.02}{\sqrt{3}} \right] - f \left[0.93 - \frac{0.02}{\sqrt{3}} \right] \right\} \right| = \left| \frac{1}{2} \{178.65 - 181.45\} \right| = 1.40 \text{ K}$$

$$144 \quad u_{\epsilon}(260) = \left| \frac{1}{2} \left\{ f \left[0.93 + \frac{0.02}{\sqrt{3}} \right] - f \left[0.93 - \frac{0.02}{\sqrt{3}} \right] \right\} \right| = \left| \frac{1}{2} \{258.29 - 262.33\} \right| = 2.02 \text{ K}$$

$$145 \quad u_{\epsilon}(385) = \left| \frac{1}{2} \left\{ f \left[0.93 + \frac{0.02}{\sqrt{3}} \right] - f \left[0.93 - \frac{0.02}{\sqrt{3}} \right] \right\} \right| = \left| \frac{1}{2} \{381.97 - 388.04\} \right| = 3.04 \text{ K}$$

146

147 The combined standard uncertainty u of the thermographic measurement is given by:

$$u(T) = \sqrt{\sum_i u_i^2(T)} = \sqrt{u_{cal}^2(T) + u_{\epsilon}^2(T)} \quad (5)$$

148 Examples:

$$149 \quad u(180) = \sqrt{u_{cal}^2(180) + u_{\epsilon}^2(180)} = \sqrt{1.56^2 + 1.40^2} = 2.10 \text{ K}$$

$$150 \quad u(260) = \sqrt{u_{cal}^2(260) + u_{\epsilon}^2(260)} = \sqrt{2.25^2 + 2.02^2} = 3.02 \text{ K}$$

$$151 \quad u(385) = \sqrt{u_{cal}^2(385) + u_{\epsilon}^2(385)} = \sqrt{3.33^2 + 3.04^2} = 4.51 \text{ K}$$

152

153 The expanded measurement uncertainty U is given by:

$$U(T) = k \cdot u(T) = k \cdot \sqrt{u_{cal}^2(T) + u_{\epsilon}^2(T)}, \text{ with a coverage factor of } k = 2 \text{ for approx.} \quad (6)$$

95 % confidence interval

154

155 Examples:

$$156 \quad U(180) = 2 \cdot u(180) = 4.19 \text{ K}$$

$$157 \quad U(260) = 2 \cdot u(260) = 6.05 \text{ K}$$

$$158 \quad U(385) = 2 \cdot u(385) = 9.02 \text{ K}$$

159

160

161 **Estimation of the measurement uncertainty of the thermocouple**

162 Type B evaluation of standard uncertainty according to ISO/IEC Guide 98-3:2008¹

163 The measurement uncertainty consists of:

164 1. The measurement uncertainty of the adjustment/calibration of the thermocouple

165 $a(T_{cal}) = \pm 1.5 \text{ K}$ and $a(T_{cal}) = \pm 0.004 \cdot T$

166 Examples are made for the respective operating temperature ranges of the printers. However,
167 the maximum real extruder temperature is 385 °C for CP(H-S). Therefore, example calculations
168 are given for 180 °C, 260°C and 385 °C:

169

170 $a(180) = \pm 0.004 \cdot 180 = \pm 0.72 \text{ K}$

171 $a(260) = \pm 0.004 \cdot 260 = \pm 1.04 \text{ K}$

172 $a(385) = \pm 0.004 \cdot 385 = \pm 1.54 \text{ K}$

173

174 2. Other aspects, e.g., environmental conditions (ambient air temperature, air humidity, etc.) may
175 also influence.

176 The thermocouple was inserted into the hotend, hence influences by environmental conditions should
177 be negligible.

178 The standard uncertainty can be calculated by assuming rectangular distribution using the equation 1
179 and 3:

$$u(T) = u(T_{cal}) = \frac{a(T_{cal})}{\sqrt{3}}$$

180

181 Examples:

182 $u(180) = \frac{0.72 \text{ K}}{\sqrt{3}} = 0.42 \text{ K}; u(260) = \frac{1.04 \text{ K}}{\sqrt{3}} = 0.60 \text{ K}; u(385) = \frac{1.54 \text{ K}}{\sqrt{3}} = 0.89 \text{ K}$

183 The expanded measurement uncertainty U is given by equation 6:

$$U(T) = k \cdot u(T), \text{ with a coverage factor of } k = 2 \text{ for approx. 95 \% confidence interval}$$

184

185 Examples:

186 $U(180) = 2 \cdot u(180) = 0.83 \text{ K}$

187 $U(260) = 2 \cdot u(260) = 1.20 \text{ K}$

188 $U(385) = 2 \cdot u(385) = 1.78 \text{ K}$

189

190 **References**

- 191 1. ISO/IEC Guide 98-3:2008. Uncertainty of measurement-Part 3: Guide to the expression of
192 uncertainty in measurement (GUM: 1995). 2008.

193