Heat Flux and Temperature Measurements on Glass Envelope and Bellows of Parabolic Trough Receivers

Simon Caron, Marc Röger, Johannes Pernpeintner (DLR)

SolarPaces Conference 2017;
Santiago, Chile; 28/09/2017
Outline

• **Introduction**
  • Measurement and Modelling

• **Heat Loss Balance**
  • Specific Heat Losses and Fluxes

• **Laboratory Setup**
  • Receiver and Shields
  • Heat Loss Test Bench
  • Scientific Instrumentation

• **Experimental Results**
  • Comparison of Receivers
  • Measurement Setup Analysis

• **Conclusion & Outlook**
## Introduction

### Measurement techniques

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<td>✅</td>
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<td>DLR (Thermorec), CIEMAT (Heatrec), CENER, NREL, IEECAS, Abengoa</td>
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<td>Microwave Induced Plasma Analytical Spectroscopy</td>
<td>Vacuum quality (H$_2$?, pressure)</td>
<td>✅</td>
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<tr>
<td>Optical characterization</td>
<td>$\alpha_s, \tau, \varepsilon_{\text{th}}$ (%)</td>
<td>✅</td>
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<td>DLR (Optirec), Abengoa (Mini Incus), CIEMAT, CENER, NREL</td>
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<tr>
<td>Transient Infrared Thermography, Inverse Heat Transfer Analysis</td>
<td>$\varepsilon_{\text{th}}$ (%), $h_{\text{ann}}$ (W/m².K), $q''_{\text{loss}}$ (W/m)</td>
<td>✅</td>
<td>✅</td>
<td>DLR</td>
</tr>
<tr>
<td>Heat Flux Sensors</td>
<td>$\dot{Q}<em>{\text{loss}}$ (W), $q''</em>{\text{loss}}$ (W/m)</td>
<td>❌</td>
<td>?</td>
<td>DLR</td>
</tr>
</tbody>
</table>
Heat Loss Balance

Receiver Heat Loss Terms

- Overall Heat Loss: $\dot{Q}_{\text{loss}} \,(\text{W})$

- $\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss, abs} - \text{gl}} + \dot{Q}_{\text{rad, abs} - \text{amb}} + \dot{Q}_{\text{loss, bellows}}$

- $\dot{Q}_{\text{loss, abs} - \text{gl}} = \dot{Q}_{\text{rad abs} - \text{gl}} + \dot{Q}_{\text{ann, abs} - \text{gl}}$
Heat Loss Balance

Receiver Heat Loss Terms

- Overall Heat Loss: $\dot{Q}_{\text{loss}}$ (W)

$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,abs-GL}} + \dot{Q}_{\text{rad,abs-amb}} + \dot{Q}_{\text{loss,bellows}}$

$\dot{Q}_{\text{loss,abs-GL}} = \dot{Q}_{\text{rad abs-GL}} + \dot{Q}_{\text{ann,abs-GL}}$
Heat Loss Balance

Receiver Heat Loss Terms

• Overall Heat Loss: \( \dot{Q}_{\text{loss}} \) (W)

\[ \dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,abs-gl}} + \dot{Q}_{\text{rad,abs-amb}} + \dot{Q}_{\text{loss,bellows}} \]

• Selective coating (Thermal emittance)

Vacuum quality

(10^{-3} \text{ mbar}: < 1\text{W})
Heat Loss Balance

Receiver Heat Loss Terms

- Overall Heat Loss: $\dot{Q}_{\text{loss}}$ (W)

- $\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,abs-}gl} + \dot{Q}_{\text{rad,abs-amb}} + \dot{Q}_{\text{loss,bellows}}$

- $\dot{Q}_{\text{loss,abs-}gl} = \dot{Q}_{\text{rad abs-}gl} + \dot{Q}_{\text{ann,abs-}gl}$

Selective coating
(Thermal emittance)
Vacuum quality
($10^{-3}$ mbar: < 1W)

- $\dot{Q}_{\text{rad,abs-amb}}$ “Spectral leakage”
  Glass semi-transparent

- $\dot{Q}_{\text{loss,bellows}}$ “Thermal bridges”
  Bellow losses
Heat Loss Balance

Receiver Heat Loss Terms

- Overall Heat Loss: $\dot{Q}_{\text{loss}}$ (W)

- $\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,abs-gl}} + \dot{Q}_{\text{rad,amb}} + \dot{Q}_{\text{loss,bellows}}$

- $\dot{Q}_{\text{loss,abs-gl}} = \dot{Q}_{\text{rad,abs-gl}} + \dot{Q}_{\text{ann,abs-gl}}$

Selectivity coating
(Thermal emittance)

Vacuum quality
($10^{-3}$ mbar: < 1W)

- $\dot{Q}_{\text{rad,abs-amb}}$
- “Spectral leakage”
- Glass semi-transparent

- $\dot{Q}_{\text{loss,bellows}}$
- “Thermal bridges”
- Bellow losses

Spectral leakage

Glass semi-transparent

Thermal bridges

Bellow losses
Heat Loss Balance

Receiver Heat Loss Terms

- Overall Heat Loss: \( \dot{Q}_{\text{loss}} \) (W)

\[
\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,abs-gl}} + \dot{Q}_{\text{rad,amb}} + \dot{Q}_{\text{loss,bellows}}
\]

- \( \dot{Q}_{\text{loss,abs-gl}} = \dot{Q}_{\text{rad,abs-gl}} + \dot{Q}_{\text{ann,abs-gl}} \)

Selectivity coating
(Thermal emittance)

- Vacuum quality
(10^{-3} mbar: < 1W)

- \( \dot{Q}_{\text{rad,abs-amb}} \)
  “Spectral leakage”
  Glass semi-transparent

- \( \dot{Q}_{\text{loss,bellows}} \)
  “Thermal bridges”
  Bellow losses
Heat Loss Balance
Specific Heat Losses and Fluxes

\[
\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss, glass}} + \dot{Q}_{\text{loss, shield,1}} + \dot{Q}_{\text{loss, shield,2}}
\]

\[
\dot{Q}_{\text{loss}}' = \frac{\dot{Q}_{\text{loss}}}{L_{\text{abs}}} \quad \dot{Q}_{\text{loss, glass}}' = \frac{\dot{Q}_{\text{loss, glass}}}{L_{\text{aperture}}} \quad \dot{Q}_{\text{loss, shield}}' = \frac{\dot{Q}_{\text{loss, shield}}}{L_{\text{shield}}}
\]

\[
\dot{Q}_{\text{loss}}'' = \frac{L_{\text{aperture}}}{L_{\text{abs}}} \cdot \dot{Q}_{\text{loss, glass}}' + 2 \cdot \frac{L_{\text{shield}}}{L_{\text{abs}}} \cdot \dot{Q}_{\text{loss, shield}}'
\]
**Laboratory Setup**

*Receivers and Shields*

- **Case 1:** Bellow expansion
- **Case 2:** Bellow compression

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**TABLE 1.** Geometrical dimensions for tested receiver tubes and corresponding shields. (*) For the absorber tube, a linear thermal expansion coefficient $a = 17 \times 10^{-6} \text{m/(mK)}$ is defined for the analysis.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Receiver 1</th>
<th>Receiver 2</th>
<th>Receiver 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{abs}}$</td>
<td>[°C]</td>
<td>20 300 400</td>
<td>20 300 400</td>
<td>20 300 400</td>
</tr>
<tr>
<td>$L_{\text{abs}}$ (*)</td>
<td>[mm]</td>
<td>4060 4080 4088</td>
<td>4060 4080 4088</td>
<td>4060 4080 4088</td>
</tr>
<tr>
<td>$L_{\text{aperture}}$</td>
<td>[mm]</td>
<td>3910 3930 3938</td>
<td>3930 3930 3930</td>
<td>3954 3954 3954</td>
</tr>
<tr>
<td>$L_{\text{shield}}$ (*)</td>
<td>[mm]</td>
<td>75 75 75</td>
<td>65 75 79</td>
<td>53 63 67</td>
</tr>
<tr>
<td>$d_{\text{glass,o}}$</td>
<td>[mm]</td>
<td>125 125 125</td>
<td>115 115 115</td>
<td>125 125 125</td>
</tr>
<tr>
<td>$d_{\text{shield,o}}$</td>
<td>[mm]</td>
<td>145 145 145</td>
<td>125 125 125</td>
<td>140 140 140</td>
</tr>
</tbody>
</table>
Laboratory Setup
Heat Loss Test Bench

\[
\dot{Q}_{\text{loss}} = P_{\text{el, main}} + P_{\text{el, bellows}}
\]

**TABLE 2. Heating configuration at ThermoRec Heat Loss Test Bench**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Material</th>
<th>Max. Power</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main heater</strong></td>
<td></td>
<td>Stainless steel</td>
<td>5 kW</td>
<td>Length: 4060 mm</td>
</tr>
<tr>
<td><strong>Bellow heaters</strong></td>
<td></td>
<td>Stainless steel</td>
<td>2x 320 W</td>
<td>Diameter: 30 mm</td>
</tr>
<tr>
<td><strong>Compensation heaters</strong></td>
<td>In use</td>
<td>Stainless steel</td>
<td></td>
<td>Length: 40 mm</td>
</tr>
<tr>
<td><strong>End insulation</strong></td>
<td></td>
<td>Cubical</td>
<td></td>
<td>Glass foam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>170 x 210 mm</td>
</tr>
</tbody>
</table>
Laboratory Setup

**Infrared camera**

- **Infrared camera:**
  - Image IR8380 (Infratec GmbH)
  - Solar blind, filter wheel
  - **Focus:** glass envelope
    - Homogeneity ?
    - Thermal bridges ?

---

**TABLE 3. IR camera specifications.**

<table>
<thead>
<tr>
<th>Optics</th>
<th>Specifications</th>
<th>Wavelength</th>
<th>Specifications</th>
<th>Temperature</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>640 x 512 pixels</td>
<td>Spectral range</td>
<td>MWIR, 2…5 μm</td>
<td>0 °C … 2000 °C</td>
<td></td>
</tr>
<tr>
<td>Objective lens</td>
<td>Wide angle (44x36°)</td>
<td>Filter 1 (Absorber)</td>
<td>Bandpass, 2.4 μm</td>
<td>+/- 1K or +/- 1 %</td>
<td></td>
</tr>
<tr>
<td>Focal length</td>
<td>12 mm</td>
<td>Filter 2 (Glass)</td>
<td>Bandpass, 3.5 μm</td>
<td>Noise @ 25°C</td>
<td>&lt; 25 mK</td>
</tr>
</tbody>
</table>

---

\[ T_{abs}: 298 \, ^{\circ}C ; T_{amb}: 19 \, ^{\circ}C ; T_{glass}: 45 \, ^{\circ}C \]

\[ T_{abs}: 348 \, ^{\circ}C ; T_{amb}: 19 \, ^{\circ}C ; T_{glass}: 55 \, ^{\circ}C \]

\[ T_{abs}: 400 \, ^{\circ}C ; T_{amb}: 19 \, ^{\circ}C ; T_{glass}: 66 \, ^{\circ}C \]
Laboratory Setup

Heat Flux Sensors

- Glass envelope: CAPTEC (FR)

- Bellows/Shields: GreenTEG XP (CH)

• First measurement setup

  - Captec HF sensor
  - gSkin-XP HF sensor
  - Thermocouple on absorber
  - Thermocouple on glass
  - Thermocouple on shield

• Second measurement setup

  - Captec HF sensor
  - gSkin-XP HF sensor
  - Thermocouple on absorber
  - Thermocouple on glass

On glass

On shield
Laboratory Setup

Heat Flux Sensors

### TABLE 4. HF sensor specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Captec sensor</th>
<th>gSkin-XP sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>30x120 mm</td>
<td>10 x10 mm</td>
</tr>
<tr>
<td>Sensing surface (mm)</td>
<td>10x90 mm</td>
<td>10x10 mm</td>
</tr>
<tr>
<td><strong>Guard zone (mm)</strong></td>
<td>Yes, 10 mm width around sensing surface</td>
<td>No guard zone</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>About 0.45 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Connector (mm)</td>
<td>10x10 mm</td>
<td>Ribbon flexprint</td>
</tr>
<tr>
<td><strong>Flexibility</strong></td>
<td>Semi-flexible, 3 rigid surfaces 10x120 mm</td>
<td>Not flexible</td>
</tr>
<tr>
<td><strong>Integrated temperature sensor</strong></td>
<td>Integrated T-type thermocouple</td>
<td>None</td>
</tr>
<tr>
<td><strong>Temperature correction required</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Relative uncertainty error (%)</strong></td>
<td>+/- 3%</td>
<td>+/- 3%</td>
</tr>
<tr>
<td>Temperature range (°C)</td>
<td>Max. range: 120°C</td>
<td>Calibration: -30/+70°C Max range: -50/+150°C</td>
</tr>
</tbody>
</table>

### TABLE 5. HF sensor sensitivity coefficients. For gSkin-XP sensors, the sensitivity \( S(T) \) at a temperature \( T(°C) \) is calculated according to the formula: \( S(T) = S_0 + (T-22.5)S_C \). (*) gSkin-XP sensor heads E4 and G3 went out of service during testing.

<table>
<thead>
<tr>
<th>Sensor model/unit</th>
<th>Captec</th>
<th>GreenTEG gSkin XP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>S [μV/(W/m²)]</td>
<td>S₀ [μV/(W/m²)]</td>
</tr>
<tr>
<td>Sensor 1</td>
<td>S = 8.05</td>
<td>H4: S₀ = 11.48</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>S = 8.18</td>
<td>D3: S₀ = 13.19</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>S = 8.36</td>
<td>E4 (*) out of service</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>S = 8.66</td>
<td>G3 (*) out of service</td>
</tr>
</tbody>
</table>
Experimental Results
Comparison of Receivers

- **Overall heat loss:**
  - \( \dot{Q}_{\text{loss, Thermoc}} \approx \dot{Q}_{\text{loss, glass, HF}} + \dot{Q}_{\text{loss, shield, HF}} \)
  - Agreement within +/- 5% (* setup #1)
  - (*): **Assumption:** Homogeneous heat flux distribution around receiver circumference

- **Specific heat loss:**
  - Trend: \( \dot{q}'_{\text{loss}} > \dot{q}'_{\text{loss, glass}} \)
  - Shielded bellows: 3-4% receiver length...
  - ... Contribution to receiver heat loss: 5 to 15%
  - More pronounced at lower absorber temperature

- **Heat flux comparison:**
  - Separation of glass envelope and shielded bellows
  - Local fluxes are not equal, but higher at bellows
Experimental Results

Comparison of Receivers

TABLE 1. Geometrical dimensions for tested receiver tubes and corresponding shields. (*) For the absorber tube, a linear thermal expansion coefficient $\alpha = 17 \times 10^{-6} \text{m/(mK)}$ is defined for the analysis.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Receiver 1</th>
<th>Receiver 2</th>
<th>Receiver 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{abs}$</td>
<td>°C</td>
<td>20</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>$L_{abs}$ (*)</td>
<td>mm</td>
<td>4060</td>
<td>4080</td>
<td>4088</td>
</tr>
<tr>
<td>$L_{aperture}$</td>
<td>mm</td>
<td>3910</td>
<td>3930</td>
<td>3938</td>
</tr>
<tr>
<td>$L_{shield}$ (*)</td>
<td>mm</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>$d_{glass}$</td>
<td>mm</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>$d_{shield}$</td>
<td>mm</td>
<td>145</td>
<td>145</td>
<td>145</td>
</tr>
</tbody>
</table>

TABLE 6. Detailed heat loss balance for all tested receivers. Heat losses derived from HF measurements agree with ThermoRec measurements within ±5 % except for receivers 2 and 3 at 400°C, assuming homogeneous heat fluxes around the receiver circumference.

<table>
<thead>
<tr>
<th>Meas. system</th>
<th>Measurand</th>
<th>Receiver 1</th>
<th>Receiver 2</th>
<th>Receiver 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThermoRec (Reference)</td>
<td>$T_{abs}$ (°C)</td>
<td>298.4</td>
<td>400.0</td>
<td>296.4</td>
</tr>
<tr>
<td></td>
<td>$P_{el,main}$ (W)</td>
<td>375</td>
<td>955</td>
<td>445</td>
</tr>
<tr>
<td></td>
<td>$P_{el,bellow}$ (W)</td>
<td>50</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>($A$) $Q_{loss,ThermoRec}$ (W)</td>
<td>$425 \pm 20$</td>
<td>$1010 \pm 40$</td>
<td>$495 \pm 20$</td>
</tr>
<tr>
<td>HF sensors</td>
<td>$Q_{loss,glass}$ (W)</td>
<td>380</td>
<td>900</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>$Q_{loss,shield}$ (W)</td>
<td>65</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>($B$) $Q_{loss,HF}$ (W)</td>
<td>$445 \pm 20$</td>
<td>$1000 \pm 50$</td>
<td>$470 \pm 30$</td>
</tr>
<tr>
<td></td>
<td>$Q_{loss,shield}/Q_{loss,HF}$ (%)</td>
<td>15%</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Comparison</td>
<td>$\Delta = (A)-(B) (W)$</td>
<td>-20</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>$\Delta/ Q_{loss,ThermoRec}$ (%)</td>
<td>-5%</td>
<td>1%</td>
<td>-5%</td>
</tr>
</tbody>
</table>
Experimental Results

Measurement Setup Analysis

• First measurement setup

- Captec HF sensor
- gSkin-XP HF sensor
- Thermocouple on absorber
- Thermocouple on glass
- Thermocouple on shield

1000 mm
1930 mm

• Second measurement setup

- Captec HF sensor
- gSkin-XP HF sensor
- Thermocouple on absorber
- Thermocouple on glass

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350 °C

TABLE 7. Comparison of HF measurement results for receiver 1, tested at an absorber temperature $T_{abs} \sim 350 ^\circ C$. Uncertainty calculations include standard deviations between sensors if available, sensor noise and manufacturer uncertainty.

<table>
<thead>
<tr>
<th>System</th>
<th>Measurand</th>
<th>Receiver 1 (Setup 1, Fig. 4.c)</th>
<th>Receiver 1 (Setup 2, Fig. 4.d, 3 runs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermorec</td>
<td>$T_{abs} \ (^\circ C)$</td>
<td>348.3°C</td>
<td>348.4°C</td>
</tr>
<tr>
<td></td>
<td>(A) $Q_{loss, Thermorec} \ (W)$</td>
<td>655 ± 25</td>
<td>655 ± 25</td>
</tr>
<tr>
<td>Captec (x2)</td>
<td>$q''_{loss, glass, top} \ (W/m^2)$</td>
<td>N.A.</td>
<td>310 ± 20</td>
</tr>
<tr>
<td>Captec (x2)</td>
<td>$q''_{loss, glass, side} \ (W/m^2)$</td>
<td>380 ± 15</td>
<td>370 ± 30</td>
</tr>
<tr>
<td>gSkin-XP</td>
<td>$q''_{loss, glass, top} \ (W/m^2)$</td>
<td>390 ± 25</td>
<td>385 ± 30</td>
</tr>
<tr>
<td>Comparison (Heat Fluxes)</td>
<td>gSkin vs. Captec (top vs. side)</td>
<td>10 W/m²</td>
<td>15 ± 5 W/m² (-17 %)</td>
</tr>
<tr>
<td></td>
<td>Captec: top (x2), vs. side (x2)</td>
<td>N.A.</td>
<td>62 W/m² (-17 %)</td>
</tr>
<tr>
<td>Captec</td>
<td>$Q_{loss, glass} \ (W)$</td>
<td>585</td>
<td>525</td>
</tr>
<tr>
<td>gSkin-XP</td>
<td>$Q_{loss, shield} \ (W)$</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Total (HF)</td>
<td>(B) $Q_{loss, HF} \ (W)$</td>
<td>665 ± 30</td>
<td>605 ± 75</td>
</tr>
<tr>
<td>Comparison (Heat Loss)</td>
<td>$\Delta = (A-B) \ (W)$</td>
<td>-10</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>$\Delta/ Q_{loss, Thermorec} \ (%)$</td>
<td>-2%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Conclusion & Outlook

• Laboratory experiments:
  • Overall heat loss:
    • Thermorec vs. HF: Agreement within +/- 5% (*)
    • Homogeneous HF distribution over circumference
    • Higher deviation with second measurement setup
  • Specific heat loss:
    • Trend: \( q'_{\text{loss}} > q'_{\text{loss, glass}} \)
    • Shielded Bellows: 3-4% Receiver Length...
    • … 5 to 15% of Receiver Heat Loss
    • More pronounced at lower absorber temp.
  • Heat flux comparison:
    • Separation of glass envelope and shielded bellows
    • Higher heat fluxes are observed at bellows

• Outlook in the field:
  • Realistic adiabatic conditions at end faces
  • Homogeneous flux distribution ?
    • Are sensors and cabling robust enough ?
  • Signal sensitive to wind gusts, more noise
  • HF sensors + IR thermography = complementary tools to investigate odd receivers

SolarPACES 2017, Santiago, Chile; September 28th 2017?
Thank you for your attention!

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- Financial support from the German Federal Ministry for Economic Affairs and Energy (BMWi) is gratefully acknowledged (QUARZ-Zert project, Contract n°0325712).