Final Report of EUROMET.T-S2 (projects EUROMET 391 and 712): Supplementary Comparison of Realizations of the Indium Freezing Point

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\textsuperscript{8}National Physical Laboratory (NPL), United Kingdom  
\textsuperscript{9}Istituto di Metrologia “G.Colonnetti” (IMGC), now Istituto Nazionale di Ricerca Metrologica, Italy  
\textsuperscript{10}JUJ, Centre de métrologie et d'accreditation (MIKES), Finland  
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\textsuperscript{13}Istituto di Metrologia “G.Colonnetti” (IMGC), now Istituto Nazionale di Ricerca Metrologica, Italy  
\textsuperscript{14}Nederlands Meetinstituut - Van Swinden Laboratory (VSL), the Netherlands  
\textsuperscript{15}Instituto Portugues da Qualidade (IPQ), Portugal  
\textsuperscript{16}Swedish National Testing and Research Institute (SP), Sweden  
\textsuperscript{17}Slovak Institute of Metrology (SMU), Slovakia  
\textsuperscript{18}University of Ljubljana (MIRS/FE-LMK), Slovenia  
\textsuperscript{19}Ulusal Metrolji Enstitusu (UME), Turkey  
\textsuperscript{20}Główny Urząd Miar (GUM), Poland

Abstract.

Comparisons of indium freezing point cells have been carried out by the EUROMET TC-THERM group as Projects Nos. 391 and 712. The main objective was to establish the agreement between the realizations of the indium freezing point within different participating laboratories, to identify and eliminate possible discrepancies. The equipment has been made available by BNM-INM. Justervesenet coordinated project no. 391, while project 712 was coordinated by BNM-INM. This paper is the final report of the results obtained, including the uncertainties in the comparisons and the degrees of equivalence between the laboratories.
INTRODUCTION

The freezing point of indium was introduced as a new fixed point in the International Temperature Scale of 1990, ITS-90 [1]. This enabled the realization of the ITS-90 and calibration of platinum resistance thermometers in the temperature range 0 °C to 156 °C at a significantly lower level of uncertainty. For EUROMET Project No. 391, a transfer indium cell (In 114) together with a furnace has been circulated among the nineteen European national laboratories listed in Table 1, for the comparison of their realizations of this fixed point. The stability of the indium cell was verified by the reference laboratory (BNM-INM) in March 1997, January 1998, February 1999, July 2000 and January 2002, and the results demonstrate that, even though the circulation was performed over a long period, the stability of the cell was satisfactory for this type of comparison.

However, during certain periods throughout the circulation, the furnace malfunctioned by not achieving the necessary temperature uniformity along the whole length of the cell. As a consequence, some of the laboratories obtained large temperature differences between the local realization and the circulating one. Therefore, in EUROMET Project No. 712, complementary comparisons were organized using the same instruments, ensuring that the furnace was working optimally. These were carried out as direct comparisons between the laboratory cell and the BNM-INM transfer cell on the premises of BNM-INM. The five participants are listed in Table 2.

Preliminary reports of the results have been published for Project 391 [2] and for Project 712 [3].

Table 1. List of participating laboratories (EUROMET 391) and the indium cells

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Country</th>
<th>Indium Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Justervesenet (JV)</td>
<td>Norway</td>
<td>Pyrocontrole In 94, sealed</td>
</tr>
<tr>
<td>Bureau National de Métrieologie-Institut national de Métrieologie (BNM-INM/CNAM)</td>
<td>France</td>
<td>Pyrocontrole In 43, sealed</td>
</tr>
<tr>
<td>Bundesamt für Eich und Vermessungswesen (BEV)</td>
<td>Austria</td>
<td>Self built, open</td>
</tr>
<tr>
<td>Service de la Metrologie (SMD)</td>
<td>Belgium</td>
<td>Pyrocontrole In 135, sealed</td>
</tr>
<tr>
<td>Swiss Federal Office of Metrology (METAS)</td>
<td>Switzerland</td>
<td>Pyrocontrole In 88, sealed</td>
</tr>
<tr>
<td>Czech Metrology Institute (CMI)</td>
<td>Czech Republic</td>
<td>Isotech In 33, sealed</td>
</tr>
<tr>
<td>Physikalisch-Technische Bundesanstalt (PTB)</td>
<td>Germany</td>
<td>Isotech In 22, sealed</td>
</tr>
<tr>
<td>Danish Technology Institute (DTI)</td>
<td>Denmark</td>
<td>NPL In 2/96, sealed</td>
</tr>
<tr>
<td>Centro Español de Metrología (CEM)</td>
<td>Spain</td>
<td>Isotech In 97, open</td>
</tr>
<tr>
<td>Hellenic Institute of Metrology (EIM)</td>
<td>Greece</td>
<td>Isotech In 49, sealed</td>
</tr>
<tr>
<td>Centre for metrology and accreditation (MIKES)</td>
<td>Finland</td>
<td>Isotech In 92, open</td>
</tr>
<tr>
<td>National Physical Laboratory (NPL)</td>
<td>UK</td>
<td>NPL In 1, open</td>
</tr>
<tr>
<td>Istituto di Metrologia “G.Colonnetti” (IMGC)</td>
<td>Italy</td>
<td>IMGC In CO1, In ICA1, open with valve for pressure control</td>
</tr>
<tr>
<td>Nederlands Meetinstituut- Van Swinden Laboratory (VSL)</td>
<td>Netherlands</td>
<td>VSL89T056, open</td>
</tr>
<tr>
<td>Instituto Portugues da Qualidade (IPQ)</td>
<td>Portugal</td>
<td>Isotech In 31, sealed</td>
</tr>
<tr>
<td>Swedish National Testing and Research Institute (SP)</td>
<td>Sweden</td>
<td>Isotech In 87, open</td>
</tr>
<tr>
<td>Slovak Institute of Metrology (SMU)</td>
<td>Slovakia</td>
<td>SMU In-801, sealed</td>
</tr>
<tr>
<td>University of Ljubljana (MIRS/FE-LMK)</td>
<td>Slovenia</td>
<td>Isotech In 86, sealed</td>
</tr>
<tr>
<td>Ulusal Metrolji Enstitusu (UME).</td>
<td>Turkey</td>
<td>NPL In 7/95, sealed</td>
</tr>
</tbody>
</table>
Table 2. List of participating laboratories (EUROMET 712) and the indium cells

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Country</th>
<th>Indium Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bureau National de Métrologie-Institut national de Métrologie (BNM-INM/CNAM)</td>
<td>France</td>
<td>Pyrocontrole In 43, sealed</td>
</tr>
<tr>
<td>Hellenic Institute of Metrology (EIM)</td>
<td>Greece</td>
<td>Isotech In 49, sealed</td>
</tr>
<tr>
<td>Czech Metrology Institute (CMI)</td>
<td>Czech Republic</td>
<td>Isotech In 33, sealed</td>
</tr>
<tr>
<td>Główny Urząd Miar (GUM)</td>
<td>Poland</td>
<td>Isotech In 12, sealed</td>
</tr>
<tr>
<td>Bundesamt für Eich und Vermessungswesen (BEV)</td>
<td>Austria</td>
<td>Isotech, In 118, sealed</td>
</tr>
</tbody>
</table>

**EQUIPMENT**

The equipment supplied by BNM-INM and circulated between the 19 laboratories of Project 391 consists of a furnace and an indium fixed-point cell, In114. The furnace was transported by usual freight, while the cell was hand-carried from one laboratory to another. For Project 712 the laboratory cells were taken to BNM-INM and the comparisons were made there.

**The Furnace**

The circulating furnace works on the forced hot air principle and is constructed according to the BNM-INM design as in Figure 1.

The furnace dimensions were modified to be suitable for freight transportation. As a consequence, it was necessary to shorten the furnace and the height became insufficient to embed the whole length of the transfer cell; thus an uncertainty contribution from the ambient temperature was included in the uncertainty budget.

**Figure 1.** Operating principle of the air furnace
The Transfer Indium Cell

The transfer cell, a sealed model, identification number In 114, was made by PYROCONTROLE under license to BNM-INM. The argon pressure inside the cell is one atmosphere when the cell is at the melting temperature of indium. For transport the cell was accommodated in a specially built carrying case. Figure 2 is a schematic diagram of the cell. The height of indium between the bottom of the well and the surface is 160 ± 5 mm.

Figure 2. The design of the transfer cell

Local Indium Cells

Tables 1 and 2 summarise the In cells that were used for the local measurements. Of these, 17 cells were sealed and 7 were open. The resistance bridges used for measurements in the laboratories were ASL-F18, Guildline 9975 and MI 6010B. For Project 391, the results were reported as resistance ratios corrected to 0 mA current. The comparisons were performed between 50 % and 80 % liquid phase and the typical duration for the freezing for the transfer cell was 2 to 6 hours, while the typical width of the plateau varied between 0.2 mK to 1.4 mK.

For Project 712 the freezing temperatures of the different cells were compared at a liquid fraction between 50 % and 90 %, and the width of the plateau was between 0.26 mK and 0.44 mK. The comparisons were again made using thermometer resistances corrected to 0 mA.
REALIZATION TECHNIQUE

Each laboratory was free to use its own procedure for the local realization of the In freezing point, consistent with the recommendations of the Supplementary Information for the ITS-90 [4]:

- ‘Indium supercools by 1 K or less, so outside nucleation is usually not necessary. After melting the ingot, the furnace temperature is stabilized a degree Celsius or so below the freezing point. When the temperature indicated by a thermometer has fallen close to the freezing point, the thermometer is withdrawn and allowed to cool for up to one minute before being replaced in the cell. The loss of heat to the thermometer is sufficient to cause rapid nucleation with the formation of a thin mantle of solid indium around the thermometer well; the plateau temperature is then quickly reached’.

It is expected that, using the technique mentioned above, freezing plateaux with durations of several hours can be obtained. The technique applied for the realization of the transfer In freezing point (cell and furnace) was included in the protocol of the comparison.

MEASUREMENT UNCERTAINTIES

The uncertainty budgets reported by the laboratories for the EUROMET Project 391 are given in Table 3. The first part includes components of uncertainty in the comparisons, \( u_1 \) to \( u_6 \), taking account of correlations in the measurements. It includes contributions from the reproducibility of the temperature differences, self-heating, perturbing heat exchanges, electrical effects, temperature variations on the plateau, and the reproducibility of the transfer cell. The reproducibility component \( u_1 \) takes into account the combined stability of the thermometer, the bridge and the standard resistor.

The second part gives the components of uncertainty, \( u_7 \) to \( u_{10} \), in the local realizations of the indium point, due to chemical impurities, gas pressure, hydrostatic effect, and the long-term reproducibility of the local cell (if assessed separately from components \( u_7 \) and \( u_8 \) for impurity and gas pressure).

As the height of the circulated furnace was not sufficient to embed the whole of the transfer cell, the internal pressure of argon in the cell depended slightly on the ambient temperatures in the different laboratories. If one assumes that those variations lie inside an interval of 5 °C (20 °C to 25 °C), it is estimated that the temperature of the transfer cell will be different by a maximum of \( \pm 0.02 \) mK.

The uncertainty contribution from the reproducibility of the transfer cell was calculated by BNM-INM from the minimum and maximum differences found relative to its cell In43, as follows:

\[
(T_{\text{In}43} - T_{\text{In}14})_{\text{Max}} - (T_{\text{In}43} - T_{\text{In}14})_{\text{Min}} = (T_{\text{In}14})_{\text{Min}} - (T_{\text{In}14})_{\text{Max}}
\]

with the result:

\[
u_{\text{reproducibility}} = \frac{|(T_{\text{In}43} - T_{\text{In}14})_{\text{Max}} - (T_{\text{In}43} - T_{\text{In}14})_{\text{Min}}|}{2 \sqrt{3}}
\]

\[
= 0.46 / 3.46 = 0.13 \text{ mK}.
\]

The component \( u_6 \) includes \( u_{\text{reproducibility}} \) and also a small contribution (\( \pm 0.02 \) mK) coming from the ambient conditions.
### Table 3. Uncertainties in the comparisons of realizations in EUROMET 391. All components are given in mK

<table>
<thead>
<tr>
<th>Component of uncertainty</th>
<th>INM</th>
<th>JV</th>
<th>METAS</th>
<th>PTB</th>
<th>VSL</th>
<th>SP</th>
<th>MIKES</th>
<th>NPL</th>
<th>IMGC</th>
<th>CEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$ Short term reproducibility</td>
<td>0.03</td>
<td>0.09</td>
<td>0.126</td>
<td>0.03</td>
<td>0.22</td>
<td>0.04</td>
<td>0.139</td>
<td>0.023</td>
<td>0.332</td>
<td>0.025</td>
</tr>
<tr>
<td>$u_2$ Self-heating</td>
<td>0.03</td>
<td>0.06</td>
<td>0.06</td>
<td>0.05</td>
<td>0.002</td>
<td>0.058</td>
<td>0.018</td>
<td>0.05</td>
<td>0.008</td>
<td>0.04</td>
</tr>
<tr>
<td>$u_3$ Perturbing heat exchanges</td>
<td>0.1</td>
<td>0.13</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.0058</td>
<td>0.004</td>
<td>0.05</td>
<td>0.18</td>
<td>0.173</td>
</tr>
<tr>
<td>$u_4$ Electrical effect</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.032</td>
<td>0.007</td>
<td>0.002</td>
<td>0.06</td>
<td>0.006</td>
<td>0.015</td>
</tr>
<tr>
<td>$u_5$ Temperature variation on the plateau</td>
<td>0.04</td>
<td>0.1</td>
<td>0.03</td>
<td>0.02</td>
<td>0.058</td>
<td>0.116</td>
<td>0.2</td>
<td>0.2</td>
<td>0.006</td>
<td>0.07</td>
</tr>
<tr>
<td>$u_6$ Reproducibility of the cell In 114 during the time of the project</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

| Standard uncertainty (sub-total) | 0.17 | 0.24 | 0.20 | 0.15 | 0.27 | 0.20 | 0.19 | 0.26 | 0.40 | 0.23 |

| Expanded uncertainty (sub-total at $k = 2$) | 0.35 | 0.48 | 0.41 | 0.30 | 0.56 | 0.40 | 0.40 | 0.51 | 0.85 | 0.47 |

| $u_7$ Purity | 0.24 | 0.33 | 0.47 | 0.26 | 0.027 | 0.40 | 0.289 | 0.29 | 0.27 | 0.23 |
| $u_8$ Gas pressure | 0.02 | 0.02 | 0.1 | 0.1 | 0.002 | 0.005 | 0.005 | 0.04 | 0.035 | 0.037 |
| $u_9$ Hydrostatic head effects | 0.01 | 0.023 | 0.01 | 0.02 | 0.019 | 0.013 | 0.019 | 0.03 | 0.006 | 0.019 |
| $u_{10}$ Long-term reproducibility of local cell | 0.10 | * | * | 0.05 | * | * | 0.3 | * | * | * |

| Standard uncertainty | 0.31 | 0.41 | 0.52 | 0.32 | 0.27 | 0.45 | 0.50 | 0.39 | 0.48 | 0.33 |

| Expanded uncertainty (total at $k = 2$) | 0.63 | 0.82 | 1.05 | 0.64 | 0.57 | 0.89 | 1.00 | 0.78 | 1.01 | 0.66 |

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$ Short term reproducibility</td>
<td>0.026</td>
<td>0.02</td>
<td>0.06</td>
<td>0.11</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.332</td>
</tr>
<tr>
<td>$u_2$ Self-heating</td>
<td>0.04</td>
<td>0.15</td>
<td>0.15</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.008</td>
</tr>
<tr>
<td>$u_3$ Perturbing heat exchanges</td>
<td>0.087</td>
<td>0.058</td>
<td>0.2</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
<td>0.04</td>
<td>0.04</td>
<td>0.1</td>
<td>0.18</td>
</tr>
<tr>
<td>$u_4$ Electrical effect</td>
<td>0.02</td>
<td>0.03</td>
<td>0.2</td>
<td>0.034</td>
<td>0.028</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.006</td>
</tr>
<tr>
<td>$u_5$ Temperature variation on the plateau</td>
<td>0.058</td>
<td>0.05</td>
<td>0.5</td>
<td>0.03</td>
<td>0.17</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.006</td>
</tr>
<tr>
<td>$u_6$ Reproducibility of the cell In 114 during the time of the project</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

| Standard uncertainty (sub-total) | 0.17 | 0.20 | 0.61 | 0.22 | 0.27 | 0.17 | 0.15 | 0.15 | 0.17 | 0.40 |

| Expanded uncertainty (sub-total at $k = 2$) | 0.35 | 0.40 | 1.22 | 0.44 | 0.57 | 0.33 | 0.30 | 0.30 | 0.35 | 0.85 |

| $u_7$ Purity | 0.235 | 0.48 | 0.8 | 0.27 | 0.47 | 0.4 | 0.80 | 0.47 | 0.24 | 0.27 |
| $u_8$ Gas pressure | 0.034 | 0.05 | 0.12 | 0.05 | 0.06 | 0.10 | 0.02 | 0.02 | 0.035 |
| $u_9$ Hydrostatic head effects | 0.019 | 0.02 | 0.02 | 0.01 | 0.02 | 0.016 | 0.01 | 0.01 | 0.01 | 0.006 |
| $u_{10}$ Long-term reproducibility of local cell | 0.026 | 0.13 | 0.10 | 0.10 | * | 0.10 | 0.10 | 0.05 | 0.10 | * |

| Standard uncertainty | 0.30 | 0.54 | 1.02 | 0.36 | 0.55 | 0.45 | 0.83 | 0.50 | 0.31 | 0.48 |

| Expanded uncertainty (total at $k = 2$) | 0.59 | 1.09 | 2.04 | 0.73 | 1.10 | 0.90 | 1.65 | 0.99 | 0.63 | 1.01 |

* this component is included in the assessment of $u_7$ and $u_8$. 
The uncertainties in EUROMET 712 are given in Table 4. The first part relates to the comparisons at BNM-INM: reproducibility, self-heating, perturbing heat exchanges, electrical effects, temperature variation on the plateau, and the reproducibility of the transfer cell In114. Most were reported in [3].

The second part relates to the realization of the indium fixed point at the five laboratories. They were also reported in [3] but they were not relevant to the cell comparisons at BNM-INM. They comprise components for the purity of the indium, the gas pressure in the cell, the hydrostatic head effect, and the long-term reproducibility of the local cell.

The BNM-INM component, $u_3$, associated with perturbing heat exchanges, is smaller than in Table 3 because the thermal characteristics (stability, uniformity, etc.) of the air-flow furnace used in EUROMET 712 was notably better in than the furnace circulated in EUROMET 391.

**Table 4.** Uncertainties in EUROMET 712: Part 1 gives the uncertainties in the comparisons at BNM-INM; Part 2 gives the additional uncertainties in the laboratory realizations. All components are in mK.

**Part 1: Uncertainties in the comparisons at BNM-INM.**

<table>
<thead>
<tr>
<th>Component of uncertainty</th>
<th>INM</th>
<th>CMI</th>
<th>GUM</th>
<th>EIM</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$ Short term reproducibility</td>
<td>0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>$u_2$ Self-heating</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$u_3$ Perturbing heat exchanges</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>$u_4$ Electrical effect</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$u_5$ Temperature variation on the plateau</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>$u_6$ Reproducibility of the cell In114 during the time of the project</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Combined uncertainty</strong></td>
<td><strong>0.09</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.12</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.12</strong></td>
</tr>
<tr>
<td><strong>Expanded uncertainty (at $k = 2$)</strong></td>
<td><strong>0.19</strong></td>
<td><strong>0.19</strong></td>
<td><strong>0.24</strong></td>
<td><strong>0.19</strong></td>
<td><strong>0.25</strong></td>
</tr>
</tbody>
</table>

**Part 2: Additional components for the local indium point realizations.**

<table>
<thead>
<tr>
<th>Component of uncertainty</th>
<th>INM</th>
<th>CMI</th>
<th>GUM</th>
<th>EIM</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_7$ Purity</td>
<td>0.24</td>
<td>0.47</td>
<td>0.55</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>$u_8$ Gas pressure</td>
<td>0.02</td>
<td>0.02</td>
<td>0.10</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>$u_9$ Hydrostatic head effects</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$u_{10}$ Long-term reproducibility of local cell</td>
<td>0.10</td>
<td>0.05</td>
<td>0.07</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Combined uncertainty (all components)</strong></td>
<td><strong>0.28</strong></td>
<td><strong>0.49</strong></td>
<td><strong>0.58</strong></td>
<td><strong>0.82</strong></td>
<td><strong>0.41</strong></td>
</tr>
<tr>
<td><strong>Expanded uncertainty (at $k = 2$)</strong></td>
<td><strong>0.55</strong></td>
<td><strong>0.98</strong></td>
<td><strong>1.15</strong></td>
<td><strong>1.64</strong></td>
<td><strong>0.82</strong></td>
</tr>
</tbody>
</table>

**RESULTS**

The laboratories reported results for EUROMET 391 as the project progressed, as is shown in Table 5 and plotted in Figure 3. They are presented as the means of the temperature differences between the local cell and the transfer cell, expressed in millikelvins. The uncertainties are the expanded total of the laboratory values in Table 3, including the contribution from the long-term reproducibility of the transfer cell. Uncertainty bars in Figure 3 are shown, both for the comparison uncertainties alone and including the local realization uncertainties.

The BNM-INM results are the reference measurements, and BNM-INM (mean) is the average of the five reference measurements. The temperature differences obtained are given in Figure 3 showing that all the differences except two lie between $-0.61$ mK and $+1.09$ mK. However, three of the laboratories (IMGC, BEV and EIM) obtained a temperature difference larger than 1 mK.
Table 5. Temperature differences, with uncertainties, between the local realization and the transfer realization of the indium freezing point in EUROMET 391. All values are given in mK.

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>BNM-INM March 1997</th>
<th>JV</th>
<th>METAS</th>
<th>BNM-INM January 1998</th>
<th>PTB</th>
<th>VSL</th>
<th>SP</th>
<th>MIKES</th>
<th>NPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{In (loc)}} - T_{\text{In (114)}}$</td>
<td>-0.36</td>
<td>-0.26</td>
<td>-0.41</td>
<td>-0.21</td>
<td>0.03</td>
<td>0.57</td>
<td>0.38</td>
<td>-0.20</td>
<td>-0.17</td>
</tr>
<tr>
<td>Uncertainty ($k = 2$)</td>
<td>0.63</td>
<td>0.82</td>
<td>1.05</td>
<td>0.63</td>
<td>0.64</td>
<td>0.57</td>
<td>0.89</td>
<td>1.00</td>
<td>0.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>IMGC</th>
<th>BNM-INM March 1999</th>
<th>BEV</th>
<th>CEM</th>
<th>IPQ</th>
<th>DTI</th>
<th>SMD</th>
<th>BNM-INM July 2000</th>
<th>UME</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{In (loc)}} - T_{\text{In (114)}}$</td>
<td>*</td>
<td>0.10</td>
<td>**</td>
<td>-0.30</td>
<td>-0.24</td>
<td>-0.59</td>
<td>-0.49</td>
<td>-0.34</td>
<td>0.11</td>
</tr>
<tr>
<td>Uncertainty ($k = 2$)</td>
<td>*</td>
<td>0.63</td>
<td>**</td>
<td>0.66</td>
<td>0.59</td>
<td>1.09</td>
<td>2.04</td>
<td>0.73</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*Withdrawn due to malfunctioning of the transfer furnace (see text and Figure 5)
**Withdrawn due to failure of the local standard.

Figure 3. The temperature differences in EUROMET 391, given in chronological order, with uncertainty bars (at $k = 2$) both for the comparison uncertainties alone, and including the local realization uncertainties.
The analysis and investigations made by IMGC (Italy) during its first period of measurements showed that the transfer furnace might not have been functioning properly during that time. The anomaly could have been provoked by disturbances from the transportation of the furnace. Measurements were performed on the temperature distribution along the thermometer well during the freezing of indium for both the local cell and the transfer cell. Figure 5 shows that the temperature distribution followed the Clausius-Clapeyron curve in the local cell, but it did not follow the same pattern in the transfer cell. On the basis of these results, IMGC was allowed to do additional measurements with the repaired furnace within Project 391.

**Figure 4.** Temperature distribution along the thermometer wells during freezing, IMGC first measurements. The full line represents the calculated hydrostatic effect.

![Figure 4](image1)

**Figure 5.** Temperature distribution along the thermometer wells during freezing (IMGC 2003). The full line represents the calculated hydrostatic effect.

![Figure 5](image2)
The later (January 2003) measurements at IMGC were performed with the same equipment, but a different cell (0.3 mK ± 0.2 mK higher), and the results are given in Table 5, last entry. The laboratory measured once more the temperature distribution along the thermometer well during freezing (Figure 5) and the results show good agreement with the calculated (Clausius-Clapeyron) dependence over the first three centimetres from the bottom of the transfer Indium cell. These data confirm that the transfer apparatus was working well the second time.

The results for Project 712 are given in Table 6 and plotted in Figure 6. The inner uncertainty bars refer to the comparisons at BNM-INM, while the larger uncertainties include the additional uncertainties relating to the realizations of the indium point at the participating laboratories.

### Table 6. Temperature differences, with uncertainties, between the local realization and the transfer realization of the indium freezing point in EUROMET 712. All values are given in mK.

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>CMI</th>
<th>GUM</th>
<th>EIM</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{(in,lab)} - T_{(In,114)}$</td>
<td>0.23</td>
<td>0.49</td>
<td>0.65</td>
<td>-0.54</td>
</tr>
<tr>
<td>Uncertainty ($k = 2$)</td>
<td>0.98</td>
<td>1.15</td>
<td>1.64</td>
<td>0.82</td>
</tr>
</tbody>
</table>

**Figure 6.** The temperature differences in EUROMET 712, with uncertainty bars (at $k = 2$) both for the comparison uncertainties alone, and including the local realization uncertainties.
DEGREES OF EQUIVALENCE

The results of the two projects have been combined and the inter-laboratory degrees of equivalence have been calculated. The differences are shown in Figure 7, and the degrees of equivalence are tabulated in Table 7 in the format of Appendix B of the BIPM KCDB. They are given as differences between pairs of laboratories, $i$ and $j$, with the combined uncertainties at $k = 2$, thus $(T_i - T_j) \pm U_{ij} / \text{mK}$. No KCRV has been derived in this project.

CONCLUSIONS

EUROMET Project No.391, the comparison of realizations of the indium freezing point, was based on the circulation of an indium cell and an airflow furnace. Nineteen European laboratories were involved in this comparison. During the comparison period the reproducibility of the transfer cell was periodically checked by comparison with another BNM-INM cell.

The results of this project give the agreement within EUROMET member countries between the different realizations of the freezing point of indium. The temperature differences $(T_{\text{local}} - T_{\text{In114}})$ obtained are mostly situated within the interval of about $\pm 1 \text{ mK}$. However, three of the laboratories appeared to obtain a value for the temperature difference larger than 1 mK. One of these could do additional measurements showing that its first results are to be discarded. Three others joined a new EUROMET Project, No. 712, together with BNM-INM and a new participant. This complementary project was carried out as a direct comparison, between the laboratory cell and the BNM-INM transfer cell on the premises of BNM-INM with the assistance of a laboratory delegate. The initial discrepancies were thus resolved.

REFERENCES

1. Preston-Thomas, H., Metrologia 27, 3-10 and 107, 1990
4. Supplementary Information for the ITS-90, BIPM, Sèvres, France, 1990, p 44
Table 7. Degrees of equivalence for EUROMET Projects 391 and 712.
Differences between pairs of laboratories, \(i\) and \(j\), with the combined uncertainties at \(k = 2\): \((T_i - T_j) \pm U_{ij} / \text{mK}.

<table>
<thead>
<tr>
<th>Laboratory (i) (\rightarrow) Laboratory (j)</th>
<th>BNM-INM</th>
<th>JV</th>
<th>METAS</th>
<th>PTB</th>
<th>VSL</th>
<th>SP</th>
<th>MIKES</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNM-INM</td>
<td>0.04</td>
<td>1.03</td>
<td>0.19</td>
<td>1.22</td>
<td>-0.25</td>
<td>0.90</td>
<td>-0.79</td>
</tr>
<tr>
<td>JV</td>
<td>-0.04</td>
<td>1.03</td>
<td>0.15</td>
<td>1.33</td>
<td>-0.29</td>
<td>1.04</td>
<td>-0.83</td>
</tr>
<tr>
<td>METAS</td>
<td>-0.19</td>
<td>1.22</td>
<td>-0.15</td>
<td>1.33</td>
<td>-0.44</td>
<td>1.23</td>
<td>-0.98</td>
</tr>
<tr>
<td>PTB</td>
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<td>0.90</td>
<td>0.29</td>
<td>1.04</td>
<td>0.44</td>
<td>1.23</td>
<td>-0.54</td>
</tr>
<tr>
<td>VSL</td>
<td>0.79</td>
<td>0.85</td>
<td>0.83</td>
<td>1.00</td>
<td>0.98</td>
<td>1.19</td>
<td>0.54</td>
</tr>
<tr>
<td>SP</td>
<td>0.60</td>
<td>1.09</td>
<td>0.64</td>
<td>1.21</td>
<td>0.79</td>
<td>1.38</td>
<td>0.35</td>
</tr>
<tr>
<td>MIKES</td>
<td>0.02</td>
<td>1.16</td>
<td>0.06</td>
<td>1.29</td>
<td>0.21</td>
<td>1.45</td>
<td>-0.23</td>
</tr>
<tr>
<td>NPL</td>
<td>0.05</td>
<td>1.00</td>
<td>0.09</td>
<td>1.13</td>
<td>0.24</td>
<td>1.31</td>
<td>-0.20</td>
</tr>
<tr>
<td>CEM</td>
<td>-0.08</td>
<td>0.91</td>
<td>-0.04</td>
<td>1.05</td>
<td>0.11</td>
<td>1.24</td>
<td>-0.33</td>
</tr>
<tr>
<td>IPQ</td>
<td>-0.02</td>
<td>0.86</td>
<td>0.02</td>
<td>1.01</td>
<td>0.17</td>
<td>1.20</td>
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</tr>
<tr>
<td>DTI</td>
<td>-0.37</td>
<td>1.26</td>
<td>-0.33</td>
<td>1.36</td>
<td>-0.18</td>
<td>1.51</td>
<td>-0.62</td>
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<tr>
<td>SMD</td>
<td>-0.27</td>
<td>2.14</td>
<td>-0.23</td>
<td>2.20</td>
<td>-0.08</td>
<td>2.29</td>
<td>-0.52</td>
</tr>
<tr>
<td>UME</td>
<td>0.33</td>
<td>0.96</td>
<td>0.37</td>
<td>1.10</td>
<td>0.52</td>
<td>1.28</td>
<td>0.08</td>
</tr>
<tr>
<td>FE-LMK</td>
<td>-0.33</td>
<td>1.27</td>
<td>-0.29</td>
<td>1.37</td>
<td>-0.14</td>
<td>1.52</td>
<td>-0.58</td>
</tr>
<tr>
<td>SMU</td>
<td>-0.39</td>
<td>1.10</td>
<td>-0.35</td>
<td>1.22</td>
<td>-0.20</td>
<td>1.38</td>
<td>-0.64</td>
</tr>
<tr>
<td>IMGC</td>
<td>-0.09</td>
<td>1.19</td>
<td>-0.05</td>
<td>1.30</td>
<td>0.10</td>
<td>1.46</td>
<td>-0.34</td>
</tr>
<tr>
<td>CMI</td>
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<td>1.17</td>
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<td>1.28</td>
<td>0.64</td>
<td>1.44</td>
<td>0.20</td>
</tr>
<tr>
<td>GUM</td>
<td>0.71</td>
<td>1.31</td>
<td>0.75</td>
<td>1.41</td>
<td>0.90</td>
<td>1.56</td>
<td>0.46</td>
</tr>
<tr>
<td>EIM</td>
<td>0.87</td>
<td>1.76</td>
<td>0.91</td>
<td>1.83</td>
<td>1.06</td>
<td>1.95</td>
<td>0.62</td>
</tr>
<tr>
<td>BEV</td>
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<td>1.03</td>
<td>-0.28</td>
<td>1.16</td>
<td>-0.13</td>
<td>1.33</td>
<td>-0.57</td>
</tr>
</tbody>
</table>
Table 7. Degrees of equivalence for EUROMET Projects 391 and 712, continued.
Differences between pairs of laboratories, $i$ and $j$, with the combined uncertainties at $k = 2$: $(T_i - T_j) \pm U_{ij} / \text{mK}$.

<table>
<thead>
<tr>
<th>Laboratory $i$</th>
<th>NPL</th>
<th>CEM</th>
<th>IPQ</th>
<th>DTI</th>
<th>SMD</th>
<th>UME</th>
<th>FE-LMK</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNM-INM</td>
<td>-0.05</td>
<td>1.00</td>
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<td>0.02</td>
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<tr>
<td>JV</td>
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<td>-0.02</td>
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<tr>
<td>PTB</td>
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<td>0.62</td>
</tr>
<tr>
<td>VSL</td>
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<td>0.32</td>
</tr>
<tr>
<td>CEM</td>
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<td>1.02</td>
<td>-0.06</td>
<td>0.99</td>
<td>0.29</td>
<td>1.27</td>
<td>0.19</td>
</tr>
<tr>
<td>IPQ</td>
<td>-0.07</td>
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<tr>
<td>DTI</td>
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<td>1.24</td>
<td>-0.10</td>
</tr>
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<td>SMD</td>
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<td>2.14</td>
<td>-0.25</td>
<td>2.12</td>
<td>0.10</td>
</tr>
<tr>
<td>UME</td>
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<td>0.35</td>
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<td>1.28</td>
<td>-0.31</td>
<td>1.25</td>
<td>0.04</td>
</tr>
<tr>
<td>SMU</td>
<td>-0.44</td>
<td>1.19</td>
<td>-0.31</td>
<td>1.12</td>
<td>-0.37</td>
<td>1.08</td>
<td>-0.02</td>
</tr>
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<td>IMGC</td>
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<td>-0.01</td>
<td>1.21</td>
<td>-0.07</td>
<td>1.17</td>
<td>0.28</td>
</tr>
<tr>
<td>CMI</td>
<td>0.40</td>
<td>1.25</td>
<td>0.53</td>
<td>1.18</td>
<td>0.47</td>
<td>1.14</td>
<td>0.82</td>
</tr>
<tr>
<td>GUM</td>
<td>0.66</td>
<td>1.39</td>
<td>0.79</td>
<td>1.33</td>
<td>0.73</td>
<td>1.29</td>
<td>1.08</td>
</tr>
<tr>
<td>EIM</td>
<td>0.82</td>
<td>1.82</td>
<td>0.95</td>
<td>1.77</td>
<td>0.89</td>
<td>1.74</td>
<td>1.24</td>
</tr>
<tr>
<td>BEV</td>
<td>-0.37</td>
<td>1.13</td>
<td>-0.24</td>
<td>1.05</td>
<td>-0.30</td>
<td>1.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Table 7. Degrees of equivalence for EUROMET Projects 391 and 712, continued.
Differences between pairs of laboratories, \( i \) and \( j \), with the combined uncertainties at \( k = 2: (T_i - T_j) \pm U_{ij} / \text{mK} \).

<table>
<thead>
<tr>
<th>Laboratory ( j ) →</th>
<th>SMU</th>
<th>IMGC</th>
<th>CMI</th>
<th>GUM</th>
<th>EIM</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNM-INM</td>
<td>0.39</td>
<td>1.10</td>
<td>0.09</td>
<td>1.19</td>
<td>-0.45</td>
<td>-0.71</td>
</tr>
<tr>
<td>JV</td>
<td>0.35</td>
<td>1.22</td>
<td>0.05</td>
<td>1.30</td>
<td>-0.49</td>
<td>-0.75</td>
</tr>
<tr>
<td>METAS</td>
<td>0.20</td>
<td>1.38</td>
<td>-0.10</td>
<td>1.46</td>
<td>-0.64</td>
<td>-0.90</td>
</tr>
<tr>
<td>PTB</td>
<td>0.64</td>
<td>1.10</td>
<td>0.34</td>
<td>1.20</td>
<td>-0.20</td>
<td>-0.46</td>
</tr>
<tr>
<td>VSL</td>
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<td>1.07</td>
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<td>1.16</td>
<td>0.34</td>
<td>1.13</td>
</tr>
<tr>
<td>SP</td>
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<td>0.69</td>
<td>1.35</td>
<td>0.15</td>
<td>1.32</td>
</tr>
<tr>
<td>MIKES</td>
<td>0.41</td>
<td>1.35</td>
<td>0.11</td>
<td>1.42</td>
<td>-0.43</td>
<td>1.40</td>
</tr>
<tr>
<td>NPL</td>
<td>0.44</td>
<td>1.19</td>
<td>0.14</td>
<td>1.28</td>
<td>-0.40</td>
<td>1.25</td>
</tr>
<tr>
<td>CEM</td>
<td>0.31</td>
<td>1.12</td>
<td>0.01</td>
<td>1.21</td>
<td>-0.53</td>
<td>1.18</td>
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