# Inter laboratory comparison on Computed Tomography for industrial applications in the slaughterhouses

CIA-CT comparison

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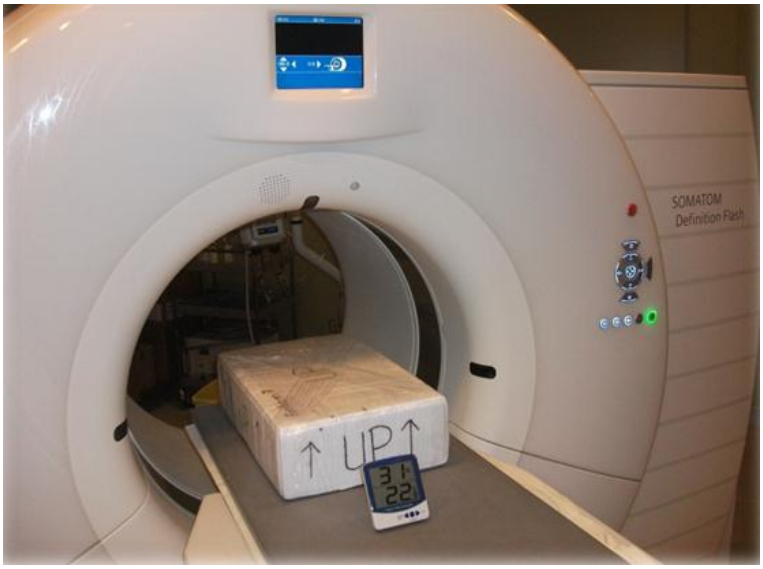


**January 2014**

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## Abstract

An intercomparison on X-ray Computed Tomography (CT) for industrial applications in the slaughterhouses was organized by the Centre for Geometrical Metrology (CGM), Department of Mechanical Engineering, Technical University of Denmark (DTU) and carried out within the project "Centre for Industrial Application of CT scanning - CIA-CT". In the comparison, 4 laboratories from 4 countries were involved, and CT scanned two synthetic phantoms, which were used instead of real pig carcasses. A phantom consists of several polymer components as Poly methyl methacrylate (PMMA), Polyethylene (PE) and Polyvinyl chloride (PVC). The polymer materials PMMA, PE and PVC represent tissue types as respectively: meat, fat, and bone. The one phantom represents a skinny pig carcass, when the other one represents a fat pig carcass with a higher content of fat (PE). The phantoms were produced through milling and cutting processes. The phantoms circulated among four participants and a total of six clinical CT scanners in Europe. The circulation took place between May 2011 and May 2012. Different volume measurands are considered, encompassing PMMA, PE, and PVC. The results of each participant are kept confidential. Each participant can identify their own results in this report using an anonymous identification number provided by the coordinator. Measuring instructions distributed by the coordinator were followed by all participants without problems. Participants carried out measurements and sent their results to the coordinator. Reference values of both phantoms were measured by Danish Meat Research Institute (DMRI) before the circulation and determined by the coordinator using the principle of water displacement. A stability investigation on the phantoms was performed through 3 reproduced measurements over a 4 month period on a clinical CT scanner under the same conditions at DMRI. Investigations confirmed that the mean variation between the three time periods were quite small, below 30 mL. ANOVA tests demonstrated that the reproduced measurements were not significant ($\alpha$=0.05), and the materials were stable enough. Depending on phantom and material, reference expanded uncertainties ($k$=2) ranging from approx. 0 mL up to approx. 10 mL were estimated. The most participants did not have any experience of how to outline uncertainty budgets. The expanded uncertainties stated by the participants are in the range 0-18 mL for both phantoms and all materials. Results by the single participants were compared with the reference values provided by the coordinator through the $E_n$ value, where $|E_n| < 1$ indicates agreement between measurement results while $|E_n| \geq 1$ shows disagreement. Out of a total of 6 single results obtained by the participants using CT scanning, 0% of the measurements yield $|E_n|$ values less than 1, and 100% larger than 1. Systematic errors were detected for some participants on some of the measured volumes. It could be due to the specified tolerances defined by the participants for segmentation of the polymer materials. It was found that scale error correction particularly should be considered for some participants. The comparison shows that CT scanning on phantoms, generally speaking, is connected with uncertainties in the range 1-1090 mL, as compared to an uncertainty range of 0-10 mL using the principle of water displacement. Each participant can use the comparison results in the report to investigate the presence of systematic errors or an underestimation of uncertainties. Statistics related to the used equipment and procedures show that participants, in general, have followed state of the art procedures for their measurements. The phantoms are suitable artefacts for CT measurements of this kind.

## Preface

The 'CIA-CT comparison - Inter laboratory comparison on Computed Tomography for industrial applications in the slaughterhouses" was organized by DTU Department of Mechanical Engineering within the Danish project "Centre for Industrial Application of CT scanning - CIA-CT", co-financed by the Danish Ministry of Science, Technology and Innovation. The project team was composed by:

Jais Angel, Ph.D. Student
Lars Bager Christensen, Senior consultant
Angela Cantatore, PostDoc
Leonardo De Chiffre, Professor

The participants involved in the comparison were:

| | |
|---|---|
| DMRI - Danish Meat Research Institute | (Denmark) |
| IFIP - Institut du Porc | (France) |
| MRI - Department of Safety and Quality of Meat | (Germany) |
| SIC - Egészségügyi Centruma | (Hungary) |

Valuable contributions were given by the following persons.

Karin T. Nielsen, DMRI
Jane Anika Skov Olsen, DMRI
Peter Vorup, DMRI
Eli Vibeke Olsen, DMRI
Thomas Juul Andersen, DMRI
Martin Vester-Christensen, Deformalyze ApS
Søren G. H. Erbou, Deformalyze ApS
Alessandro Stolfi, DTU

Thanks to all, especially to the participants, for their contributions to the project.

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# 1. Project

The project was organized and coordinated by the Centre for Geometrical Metrology (CGM), taking advantage of previous experience in other inter laboratory comparisons [Hansen et al., 1996] [De Chiffre et al., 2004] [Angel et al., 2012].

Two synthetic phantoms were used instead of real pig carcasses for circulation: a skinny pig carcass (Phantom 1) and a fat pig carcass (Phantom 2). The phantoms were measured by 4 participants from Denmark, France, Germany and Hungary. The circulation took place between May 2011 and May 2012.

The phantoms were measured according to a protocol provided by the coordinator containing documentation, logistics, and measuring and reporting instructions [Technical Protocol]. The protocol also included reporting forms to fill out. The results of each participant are kept confidential. Each participant can identify their own results in this report using an anonymous identification number provided by the coordinator.

## 1.1. Project aims

The comparison has aimed to collect information about measurement performance in state-of the-art X-ray Computed Tomography (CT) for industrial applications in the slaughterhouses. Since CT has entered the field of industrial applications in the slaughterhouses as automated dissection of large batches of pig carcasses, evaluation of uncertainty of measurement with assessment of all influence contributors has become a most important challenge related to the establishment of traceability. This investigation focuses mainly on operator influences on the measurement result. The main goals of the project can be summarized as follows:

- To test applicability of CT for volume measurement on polymer objects, which represent pig carcasses that were commonly measured in slaughterhouses.
- To evaluate the impact of instrument settings and operator decisions on the measurement of synthetic phantoms of three different materials and geometries.
- To investigate measurement errors and their causes.
- To collect and share knowledge on practical aspects related to the traceability of measurements using CT for industrial applications in the slaughterhouses.

## 1.2. Project management and time schedule

The involved project phases were:

1. Plan, participants' definition.
2. Phantom calibrations.
3. Circulation.
4. Analysis of results.
5. Reporting and dissemination.

The timeline in Figure 1 gives an indication of the different phases.

A final workshop was held at DTU the 15th January 2013, where the participants have discussed and given contributions to the analysis of the comparison.

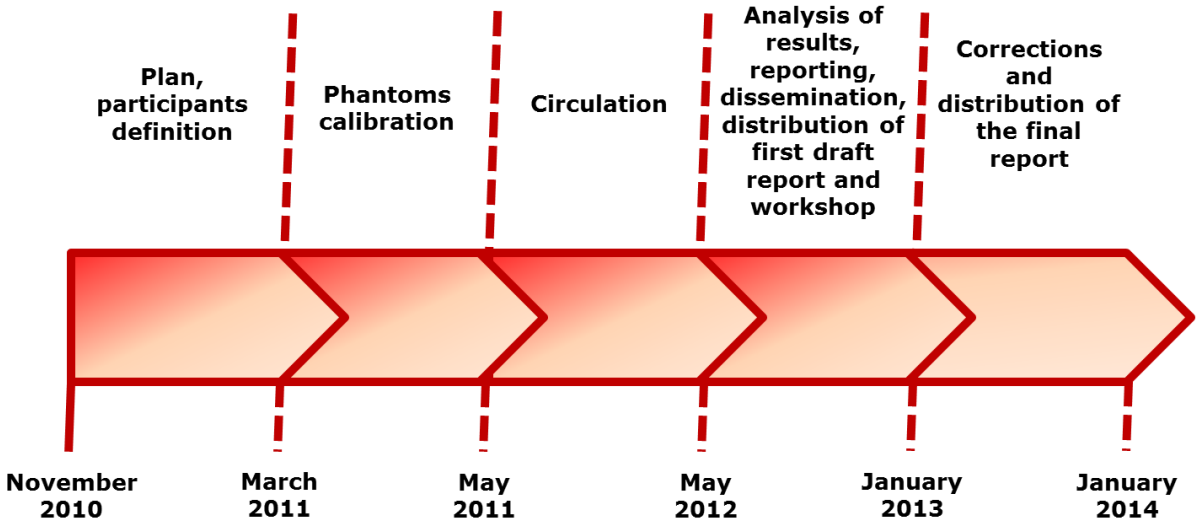


*Figure 1: Time schedule for the CIA-CT comparison.*

## 1.3. Participants

A total number of 6 clinical CT scanners from Denmark (1 scanner), France (1 scanner), Germany (1 scanner) and Hungary (3 scanners) took part in the comparison. A map showing the locations of the participants is given in Figure 2 and an overview of the participants in alphabetic order is given in Table 1. The order of the participants in Table 1 is not related to the personal identification numbers provided separately by the coordinator. One of the participants (Danish Meat Research Institute) contributed with two identification numbers (where the one identification number was using automatic software for volume determination and another identification number was using manual software). It results in a total number of seven identification numbers.


*Figure 2: The 4 participants in the CIA-CT circulation.*

*Table 1: List of the participants in the circulation in alphabetic order.*

| Participant | Country |
|---|---|
| Danish Meat Research Institute (DMRI) | Denmark |
| IFIP-Institut du Porc | France |
| MRI - Department of Safety and Quality of Meat | Germany |
| SIC Egészségügyi Centruma | Hungary |

## 1.4. Phantoms

Two synthetic phantoms representing real pig carcasses were used, a skinny pig carcass (Phantom 1) and a fat pig carcass (Phantom 2), see fat distribution in Figure 3. A phantom consists of several components (polymers). A phantom is shown in Figure 4. A phantom consists of several polymer components as Poly methyl methacrylate (PMMA), Polyethylene (PE) and Polyvinyl chloride (PVC). The polymer materials PMMA, PE and PVC represent tissue types as respectively: meat, fat, and bone. The polymer materials can be identified through their colour codes, see Figure 5. The colours are as follows: transparency (PMMA), white (PE) and black (PVC). The two phantoms are considered more similar to tissue types, in terms of material densities, volumes and geometrical properties, than reference artefacts commonly used for calibration and verification of CT scanners. Regarding to the circulation it was important to avoid damages and limit contamination of the phantoms, so they were sealed and wrapped in flamingo boxes, and then kept in suitcases, see Figure 6. It was documented that the sealing and wrapping materials did not perform any noise on the CT scanned materials in a phantom [Appendix 7.2].

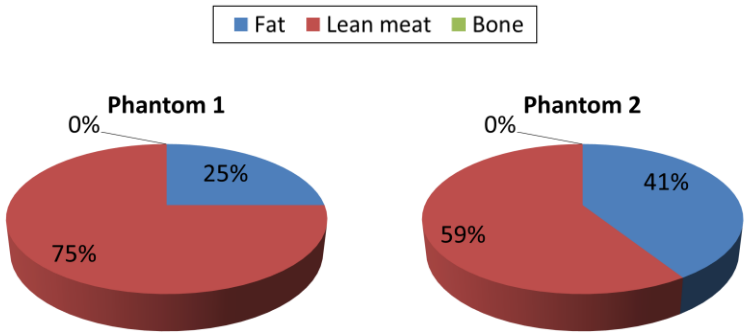


*Figure 3: Approximated fat distribution in a skinny (Phantom 1) and a fat (Phantom 2) pig carcass.*

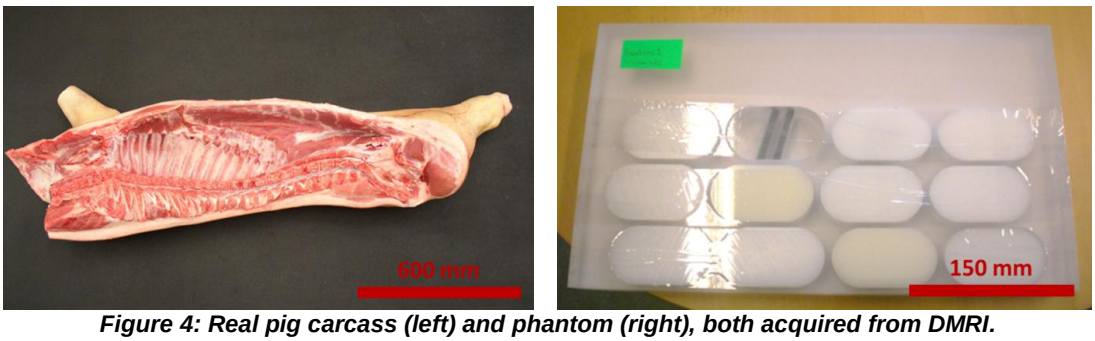


*Figure 4: Real pig carcass (left) and phantom (right), both acquired from DMRI.*

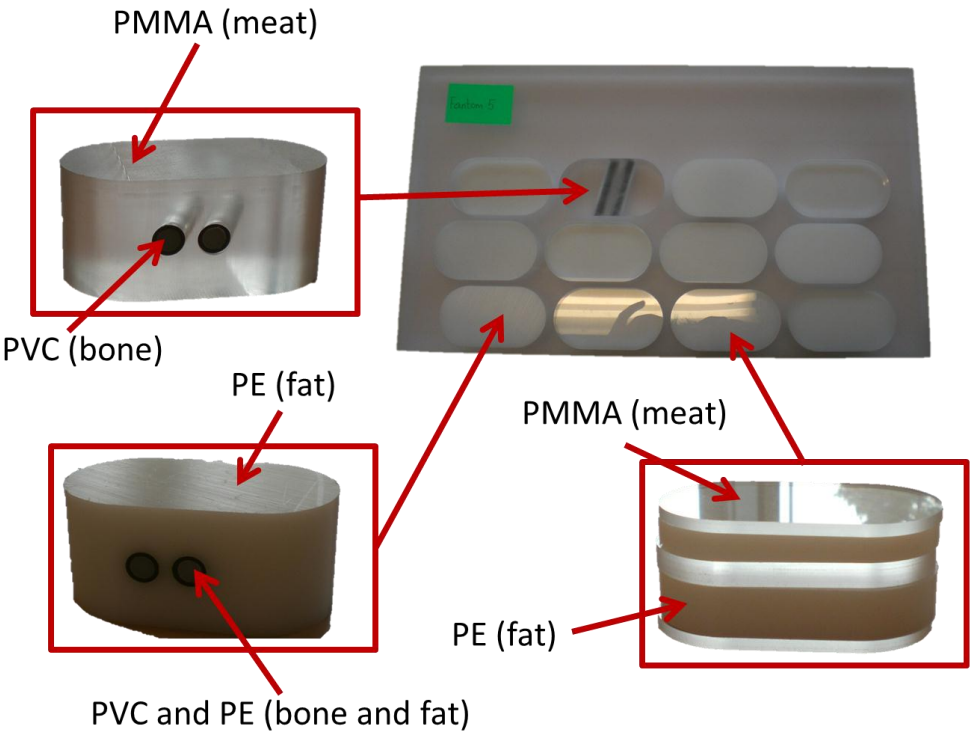


*Figure 5: Identification of polymer materials through their colour codes. The colours are as follows: transparency (PMMA), white (PE) and black (PVC). Acquired from DMRI.*


*Figure 6: Internal flamingo box containing a phantom and an external box for storage and transportation.*

## 2. Measurement procedures

The participants were responsible for following measurement procedures and instructions prepared by the project coordinator [Technical Protocol] and distributed by email before starting the circulation. The protocol includes documents which should be filled out (Template is shown in Appendix 7.1). The selection of CT scanning parameters was left to the participants' choice, to avoid limitation of their capabilities, and because it was impossible to specify the scanning parameters, when different CT scanners were involved in the comparison. The selected features were volumes of the three polymer materials (PMMA, PE and PVC) in the phantoms.

## 3. Reference values

Reference values are presented in [Appendix 7.3].

The phantoms were measured by DMRI before the circulation and determined by CGM. The phantoms were calibrated by water displacement through a method of finding the absolute density [DIN EN 725-7, 1996] [Appendix 7.4]. A pycnometer (Figure 7) was used for determination of specific gravity weight per unit volume of the used liquid (distil water). A technical weight (Figure 7) was used for weighting of the measured objects. A thermometer and a barometer were used for compensation of the results for the interaction of temperature and atmospheric pressure changes respectively. Weights with certificate were used as weight references to generate traceability. The influence of surface tension from distil water was assumed to be neglected. Each phantom features three measurands, identified as the volumes of PMMA, PE and PVC.


***Figure 7: Left: Pycnometer of the type SCHOTT DURAN 1000 mL. Right: Technical weight of the type Satorius BP 3100 S.***

Stability of the phantoms was documented through comparison of 3 reproduced measurements over a 4 month period on a clinical CT scanner under the same conditions at DMRI. Investigations confirmed that the mean variation between the three time periods were quite small, below 30 mL. ANOVA tests demonstrated that the reproduced measurements were not significant ($\alpha$=0.05), and the materials were stable enough [Appendix 7.3].

A practical approach inspired by [ISO 14253-2, 2011] was used for uncertainty estimation, as a simplification of the GUM approach [ISO/IEC Guide 98-3, 2008]. Considered uncertainty contributions can be found in [Appendix 7.3]. The calculated reference values and their corresponding uncertainties are shown in Table 2.

***Table 2: Phantoms – Reference values and their corresponding expanded uncertainties (k=2). Values are in mL.***

| | PMMA | | PE | | PVC | |
|---|---|---|---|---|---|---|
| Phantom no. | Y | U | Y | U | Y | U |
| 1 | 3896.8 | 9.8 | 1275.8 | 4.1 | 7.8 | 0.1 |
| 2 | 3055.3 | 6.3 | 2118.3 | 0.9 | 7.7 | 0.0 |

# 4. Analysis of participants' data

The measurements carried out by the participants on the clinical CT scanners are presented and their data analyses illustrated in this chapter. Not all participants have measured all measurands on both items.

## 4.1. Measurements carried out by participants

Information on set-up data is provided in the Measurement Report for each phantom, with the main subjects shown in Table 3.

***Table 3: Main subjects in the Measurement Report.***

| |
|---|
| GENERAL INFORMATION |
| CT SCANNER |
| SOFTWARE |
| SETUP AND SCANNING |
| PROCESSING PARAMETERS |
| UNCERTAINTY ASSESSMENT |
| ATTACHMENTS |

Participant's results are presented in the following. Analyses were performed for the following subjects:

- Main results for Phantom 1.
- Main results for Phantom 2.
- Agreement between participant results and reference measurements.
- Involved clinical CT scanners by the participants.
- Applied software by the participants.
- Impact of instrument settings and operator.
- Applied uncertainties by the participants.

## 4.2. Main results for Phantom 1

Participants' values and their corresponding uncertainties are shown in Table 4

Main results are shown for PMMA, PE and PVC in Figure 8, Figure 9 and Figure 10.

Only ID no. 4 had stated the uncertainties. It was because the most participants did not have any experience of how to outline uncertainty budgets.

There was a trend for the case of PMMA for Phantom 1, where the measured volume by the participants seems to become lower compared to the reference value, with a maximum difference of 466 mL. Furthermore there was a trend for the case of PE for Phantom 1, where the measured volume by the participants seems to become higher compared to the reference value, with a maximum difference of 359 mL. The measured values by the participants seem to be overestimated compared to the reference value for PVC for Phantom 1, with a maximum difference of 25 mL. The reason to these trends could be due to the specified tolerances defined by the participants for segmentation of the polymer materials. The segmentation areas between the polymer materials compose of mixed pixel values, which make it difficult to evaluate which batch they should belong.

A way to identify if a participant has segmentation problems or miss to correct for scale errors, the total volume of the phantom can be used. In Figure 11, the total volume deviation from the reference value is shown. It is clear that scale error correction particularly should be considered for ID no. 1 and 7 compared to the other IDs.

***Table 4: Phantom 1 – Participants' values and their corresponding uncertainties. Values are in mL.***

| | PMMA | | PE | | PVC | |
|---|---|---|---|---|---|---|
| ID no. | Y | U | Y | U | Y | U |
| 1 | 3945.0 | N/A | 1635.0 | N/A | 33.0 | N/A |
| 2 | 3853.9 | N/A | 1244.2 | N/A | 8.3 | N/A |
| 3 | 3890.8 | N/A | 1255.3 | N/A | 8.3 | N/A |
| 4 | 3755.8 | 6.0 | 1400.8 | 6.8 | 11.0 | 0.1 |
| 5 | 3761.0 | N/A | 1402.0 | N/A | 8.2 | N/A |
| 6 | 3854.7 | N/A | 1275.7 | N/A | 8.3 | N/A |
| 7 | 3430.5 | N/A | 1472.0 | N/A | 9.3 | N/A |
| | | | | | | |
| **MAX** | 3945.0 | 6.0 | 1635.0 | 6.8 | 33.0 | 0.1 |
| **AVG** | 3784.5 | 6.0 | 1383.6 | 6.8 | 12.3 | 0.1 |
| **MIN** | 3430.5 | 6.0 | 1244.2 | 6.8 | 8.2 | 0.1 |

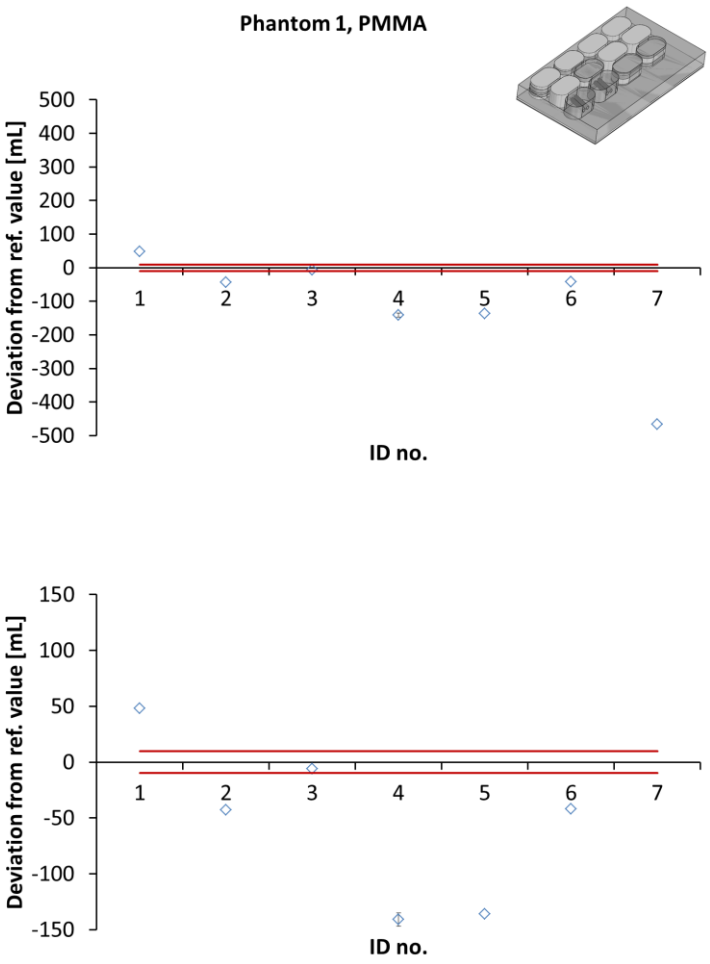


***Figure 8: Results for Phantom 1. PMMA. Top: deviation range ± 500 mL. Bottom: deviation range ± 150 mL. . The red lines indicate the maximum reference uncertainty.***

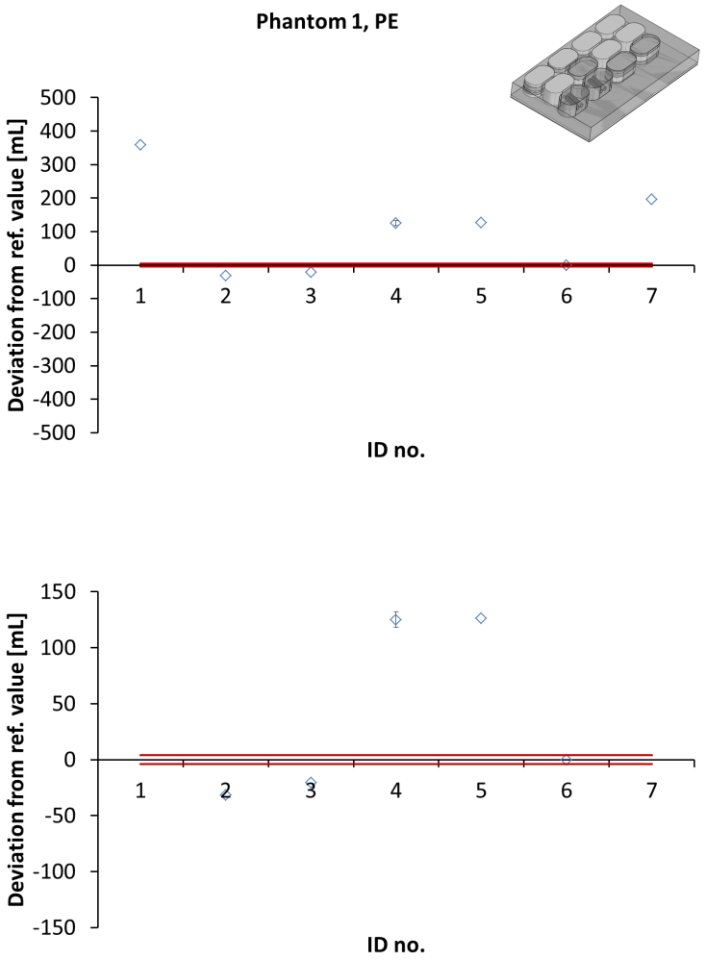


***Figure 9: Results for Phantom 1. PE. Top: deviation range ± 500 mL. Bottom: deviation range ± 150 mL. The red lines indicate the maximum reference uncertainty.***

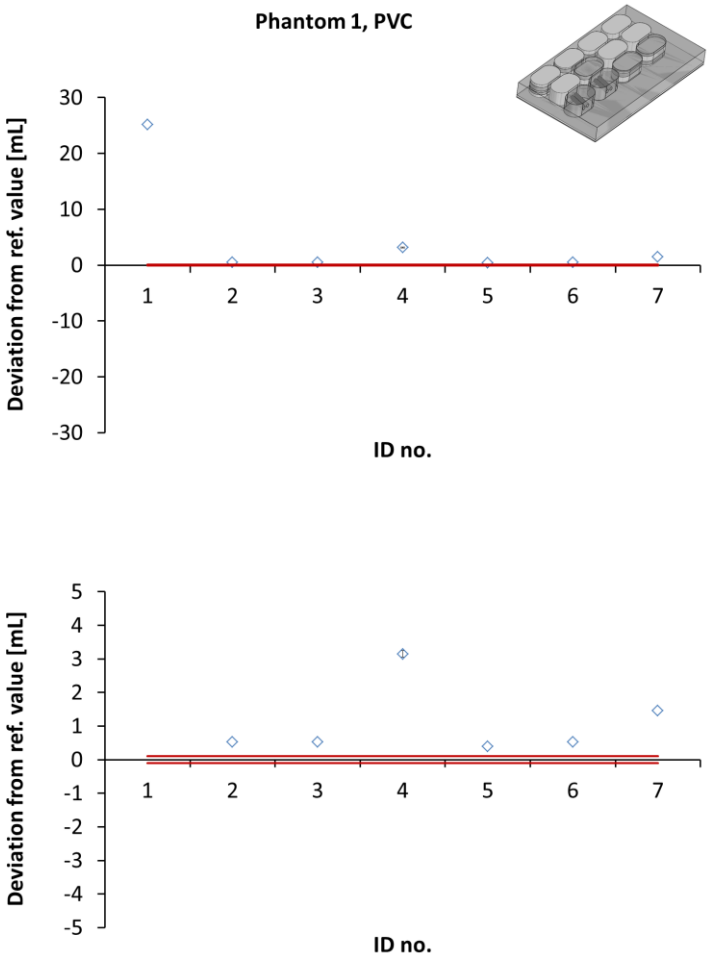


***Figure 10: Results for Phantom 1. PVC. Top: deviation range ± 30 mL. Bottom: deviation range ± 5 mL. The red lines indicate the maximum reference uncertainty.***

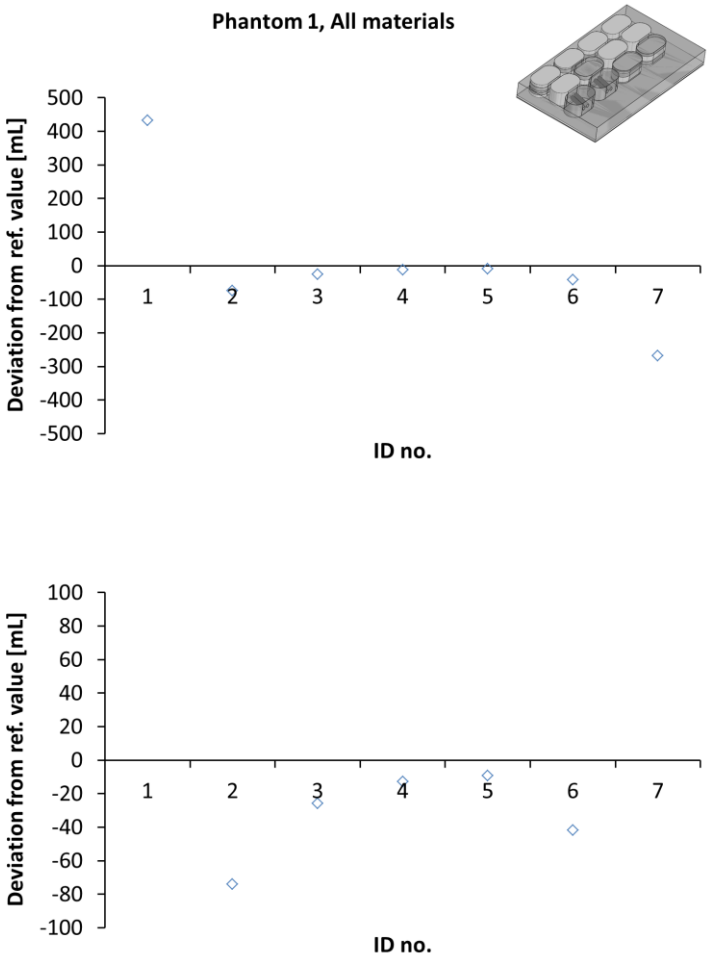


***Figure 11: Results for Phantom 1. All materials. Top: deviation range ± 500 mL. Bottom: deviation range ± 100 mL.***

## 4.3. Main results for Phantom 2

Participants' values and their corresponding uncertainties are shown in Table 5.

Main results are shown for PMMA, PE and PVC in Figure 12, Figure 13 and Figure 14.

Only ID no. 4 had stated the uncertainties. It was because the most participants did not have any experience of how to outline uncertainty budgets.

There was a trend for the case of PMMA for Phantom 2, where the measured volume by the participants seems to become lower compared to the reference value, with a maximum difference of 752 mL. Furthermore there was a trend for the case of PE for Phantom 2, where the measured volume by the participants seems to become higher compared to the reference value, with a maximum difference of 492 mL. The measured values by the participants seem to be overestimated compared to the reference value for PVC for Phantom 2, with a maximum difference of 19 mL. The reasons to these trends are the same as already described for Phantom 1 in section 4.2. Furthermore it is detected that some IDs measure incorrectly (as in section 4.2). The total

volume deviation from the reference value is shown in Figure 15. It is again clear that scale error correction particularly should be considered for ID no. 1 and 7 compared to the other IDs.

***Table 5: Phantom 2 – Participants' values and their corresponding uncertainties. Values are in mL.***

| | PMMA | | PE | | PVC | |
|---|---|---|---|---|---|---|
| ID no. | Y | U | Y | U | Y | U |
| 1 | 3015.0 | N/A | 2586.0 | N/A | 27.0 | N/A |
| 2 | 2884.9 | N/A | 2230.0 | N/A | 8.3 | N/A |
| 3 | 2920.0 | N/A | 2231.7 | N/A | 8.3 | N/A |
| 4 | 2797.4 | 11.4 | 2368.1 | 17.5 | 11.0 | 0.1 |
| 5 | 2894.0 | N/A | 2249.0 | N/A | 9.0 | N/A |
| 6 | 2943.9 | N/A | 2209.0 | N/A | 8.3 | N/A |
| 7 | 2303.7 | N/A | 2610.6 | N/A | 4.9 | N/A |
| | | | | | | |
| **MAX** | 3015.0 | 11.4 | 2610.6 | 17.5 | 27.0 | 0.1 |
| **AVG** | 2822.7 | 11.4 | 2354.9 | 17.5 | 11.0 | 0.1 |
| **MIN** | 2303.7 | 11.4 | 2209.0 | 17.5 | 4.9 | 0.1 |

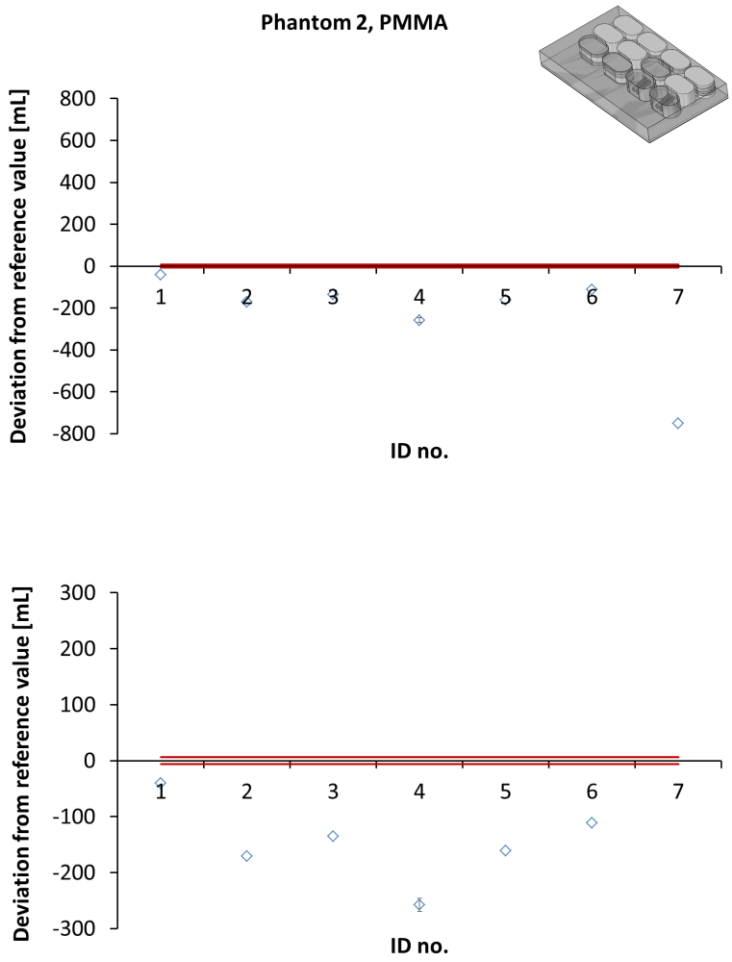


***Figure 12: Results for Phantom 2. PMMA. Top: deviation range ± 800 mL. Bottom: deviation range ± 300 mL. The red lines indicate the maximum reference uncertainty.***

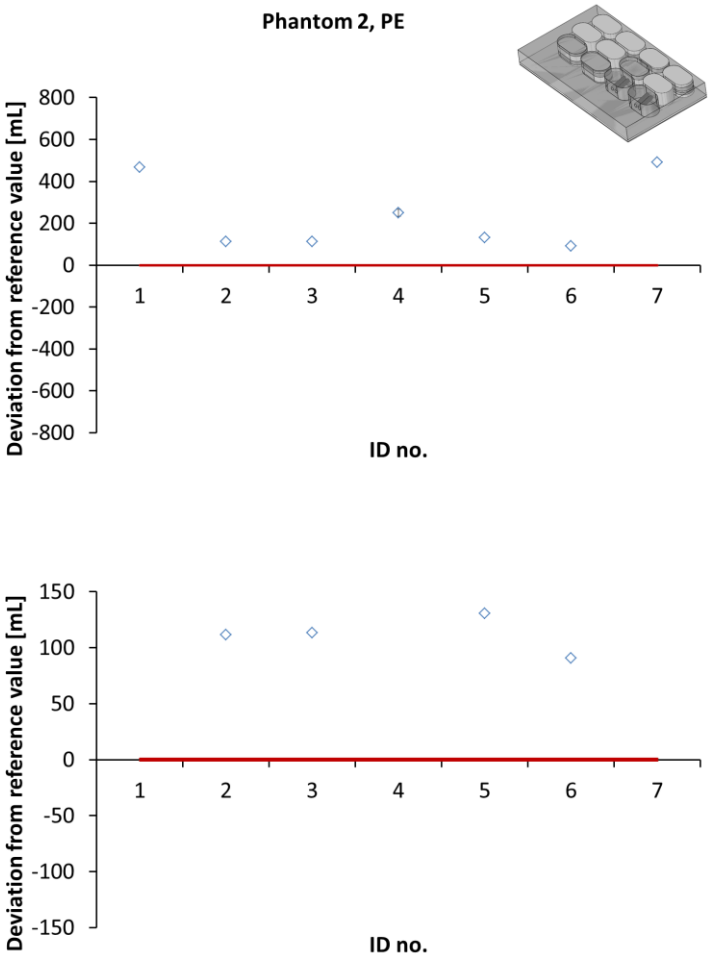


***Figure 13: Results for Phantom 2. PE. Top: deviation range ± 800 mL. Bottom: deviation range ± 150 mL. The red lines indicate the maximum reference uncertainty.***

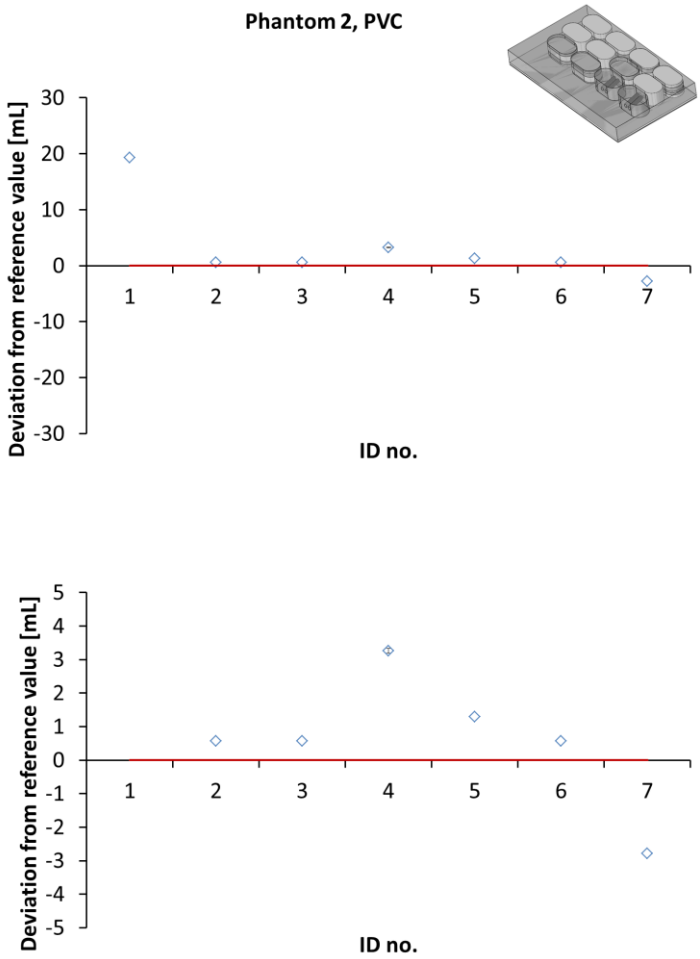


***Figure 14: Results for Phantom 2. PVC. Top: deviation range ± 30 mL. Bottom: deviation range ± 5 mL. The red lines indicate the maximum reference uncertainty.***

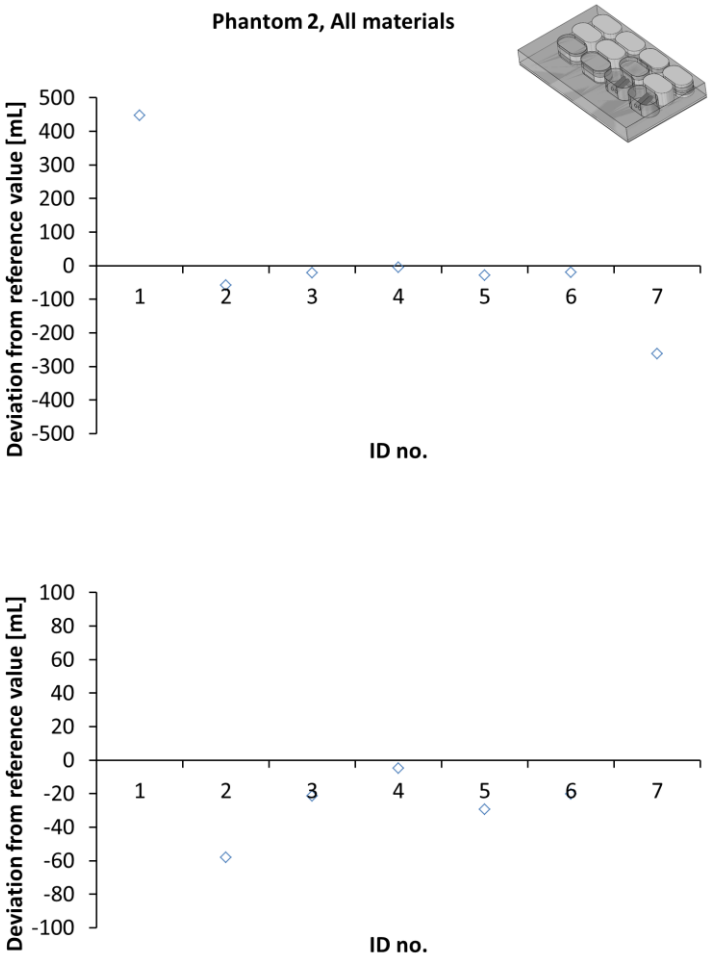


***Figure 15: Results for Phantom 2. All materials. Top: deviation range ± 500 mL. Bottom: deviation range ± 100 mL.***

## 4.4. Agreement between participant results and reference measurements

In order to judge the agreement between reference measurements and participant measurements, the $E_n$ value normalised with respect to the stated uncertainty was computed according to ISO guidelines [ISO/IEC 17043, 2010], see (4.1). If $|E_n| < 1$, agreement between reference measurement results participant results is proven, while it is not the case if $|E_n| \geq 1$.

$$E_n = \frac{x_{lab} - x_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}} \qquad \textbf{(4.1)}$$

Here, $x_{lab}$ is the measurement obtained by the participant and $x_{ref}$ the reference value, while $U_{lab}$ and $U_{ref}$ are the corresponding expanded uncertainties.

Disagreement can be caused by systematic errors in the measurement and those related to the uncertainty estimate. Each participant can extract information from the graphs in Figure 8, Figure 9, Figure 10, Figure 12, Figure 13 and Figure 14.

The reason to the differences between participants' results and the reference values could be due to four different reasons: 1) The segmentation areas between multi materials compose of mixed pixel values, which make it difficult to evaluate which batch they should belong; 2) disagreements between reference values and participants results occurs with increasing slice width and small volume determination (in this case for PVC volumes); 3) the most participants did not have any experience of how to outline uncertainty budgets; 4) Some participants measure incorrectly (operator errors).

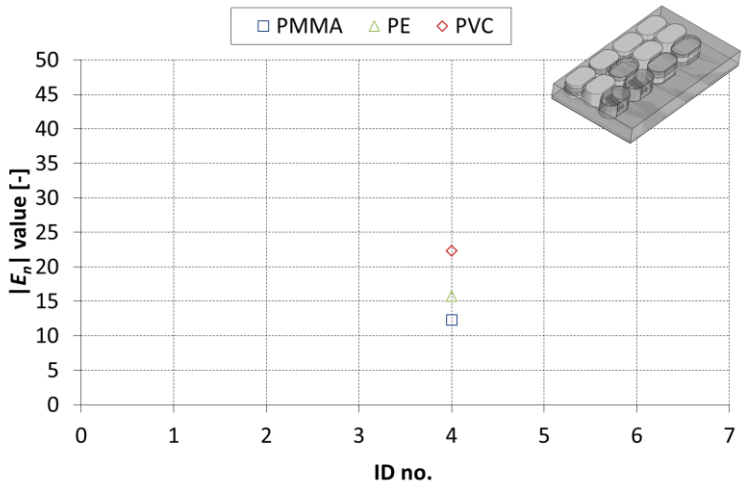


***Figure 16: $E_n$ results for Phantom 1 for all materials.***

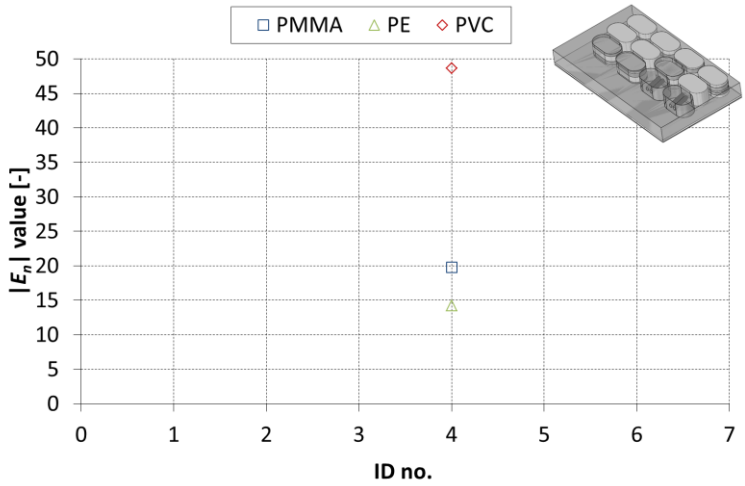


***Figure 17: $E_n$ results for Phantom 2 for all materials.***

A histogram showing the distribution of all $E_n$ values calculated for Phantom 1 and Phantom 2 is shown in Figure 18 and the distribution in percentage is shown in Table 6, and 0 % of the main results are in agreement with the reference values.

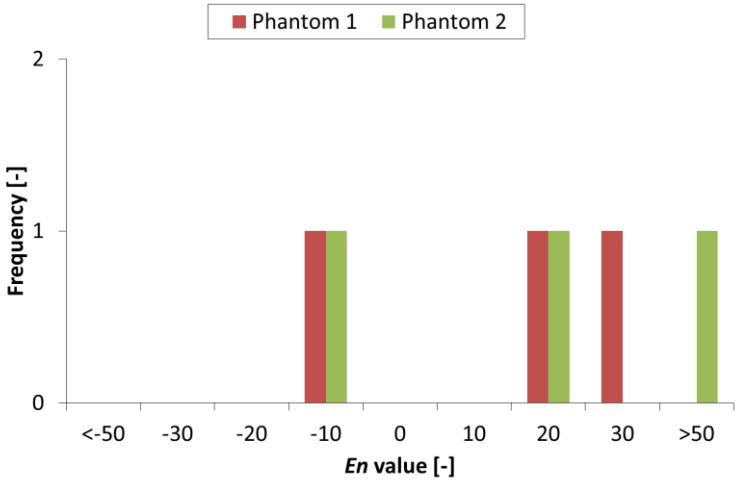


***Figure 18: Histogram for the distribution of all $E_n$ values acquired for Phantom 1 and Phantom 2.***

***Table 6: Overview of the distribution of $E_n$ values in percentage.***

| Type of measurement results | Number of measurement results | Percentage [%] |
|---|---|---|
| $\|E_n\| < 1$ | 0 | 0 |
| $\|E_n\| > 1$ | 6 | 100 |
| TOTAL | 6 | 100 |

An estimation of new uncertainties leading to $|E_n| = 0.99$ was carried out for the results with $|E_n|$ values larger than 1 and for the participants which did not stated uncertainties, see Table 7. Some results were identified as outliers using the interquartile rule for outliers [Johnson, 2005], and excluded from calculations. Outliers are marked with italic in Table 7. It was concluded that likely uncertainties for the laboratories considered in Table 7 would lie in the range 1-1090 mL. This approach is limited by the fact that all deviations are treated as random, including systematic errors, yet it clearly indicates that uncertainties of 0-17.5 mL stated by the participants are underestimated.

***Table 7: Estimation of new uncertainties leading to $|E_n| = 0.99$ for the results with $|E_n|$ values larger than 1. Values in mL. Identified outliers are shown in italic. AVG, MAX and MIN are calculated excluding outliers.***

| | Phantom 1 | | | Phantom 2 | | |
|---|---|---|---|---|---|---|
| ID no. | PMMA | PE | PVC | PMMA | PE | PVC |
| 1 | 47.7 | 362.8 | *25.5* | 890.7 | 1323.4 | *19.4* |
| 2 | 42.2 | 31.6 | 0.5 | 1022.0 | 963.8 | 0.5 |
| 3 | 7.7 | 20.3 | 0.5 | 986.7 | 965.6 | 0.5 |
| 4 | 142.0 | 126.2 | 3.2 | 1110.4 | 1103.3 | 3.2 |
| 5 | 136.8 | 127.4 | 0.4 | 1012.9 | 983.0 | 1.2 |
| 6 | 41.3 | 4.1 | 0.5 | 962.4 | 942.6 | 0.5 |
| 7 | *470.9* | 198.1 | 1.5 | *1609.2* | 1348.2 | 2.9 |
| **MAX** | 142.0 | 362.8 | 3.2 | 1110.4 | 1348.2 | 3.2 |
| **AVG** | 69.6 | 124.4 | 1.1 | 997.5 | 1090.0 | 1.5 |
| **MIN** | 7.7 | 4.1 | 0.4 | 890.7 | 942.6 | 0.5 |

## 4.5. Involved clinical CT scanners by the participants

The frequency of instrument types is shown in Figure 19.

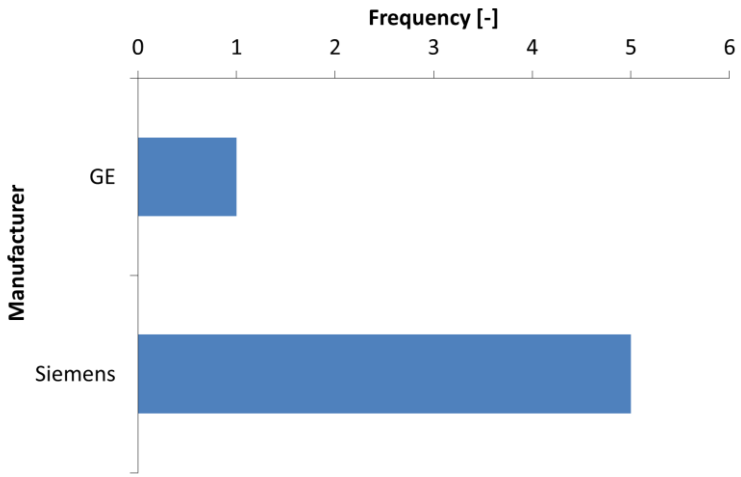


***Figure 19: Frequency of instrument types.***

## 4.6. Applied software by the participants

3 out of 6 participants had acquisition software of the type C++, see Figure 20. 4 out of 6 participants had reconstruction software of the type SyngoCT, see Figure 21. 3 out of 7 IDs had analysis software of the type C++, see Figure 22.

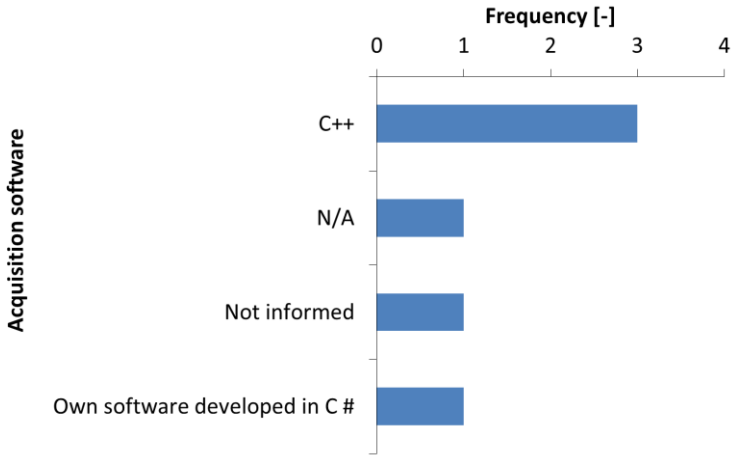


***Figure 20: Frequency of acquisition software.***

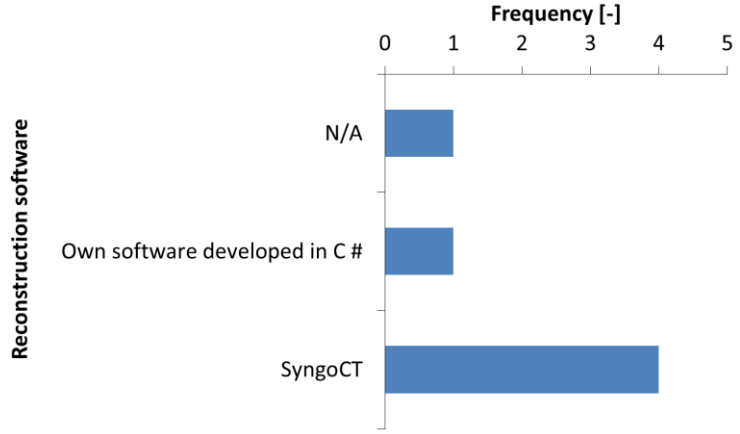


***Figure 21: Frequency of reconstruction software.***

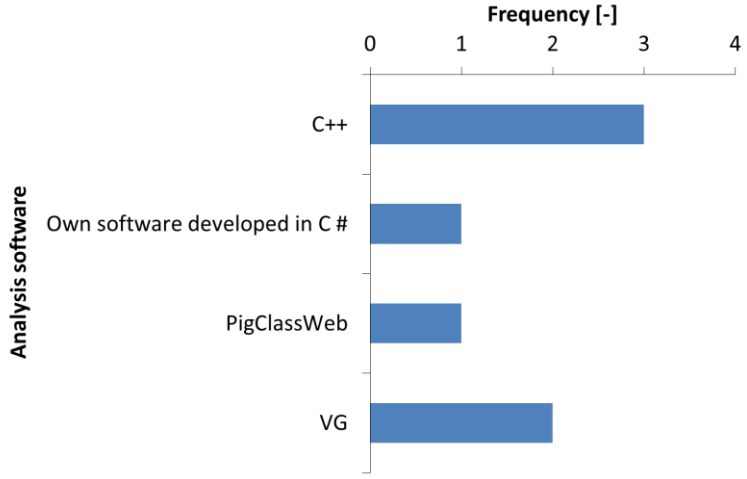


***Figure 22: Frequency of analysis software.***

## 4.7. Impact of instrument settings and operator

All 6 participants had used a helical scanner, see Figure 23. The temperature conditions inside the CT scanner by the participants are reported in Figure 24. The phantoms were scanned three times by all the participants, see Figure 25. 3 out of 6 participants had corrected for scale error correction, see Figure 26. Current versus voltage is shown in Figure 27. Deviation from reference values vs. focus spot size is shown in Figure 28 for Phantom 1 and Figure 29 for Phantom 2. The data for source-detector distance *SDD* and source-object distance *SOD* are not shown in this report, but these factors are involved in the calculations for the geometrical magnification *m*, see (4.2).

$$m = \left( \frac{SDD}{SOD} \right) \qquad \textbf{(4.2)}$$

Deviations from reference values vs. magnification are shown in Figure 30 for Phantom 1 and Figure 31 for Phantom 2. Applied slice widths by the participants is reported in Table 8. Frequency

of time per single scan is shown in Figure 32. Frequency of artefacts for scale error correction is shown in Figure 33. Deviations from reference values vs. time per 360° rotation are shown in Figure 34 for Phantom 1 and Figure 35 for Phantom 2. Deviations from reference values vs. number of revolutions (360° rotations) are shown in Figure 36 for Phantom 1 and Figure 37 for Phantom 2. Frequency of system pulsed is shown in Figure 38. Frequency of duration of single pulses is shown in Figure 39. Frequency of duration of pulses per second is shown in Figure 40. Frequency of number of projections is shown in Figure 41. Frequency of target material is shown in Figure 42. 3 out of 6 participants had performed a temperature correction, see Figure 43. 5 out of 6 participants had not performed a beam hardening correction, see Figure 44Figure 41. Frequency of filtering type and applied one is shown in Figure 45. Frequency of applied threshold methods is shown in Figure 46.

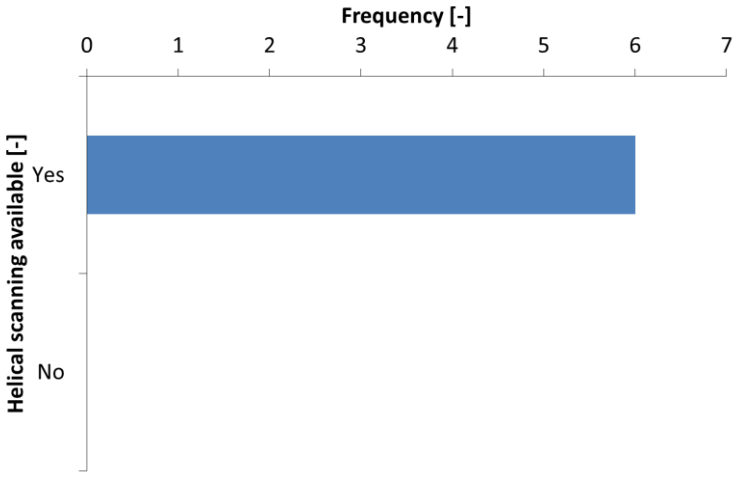


***Figure 23: Frequency of helical scanning available.***

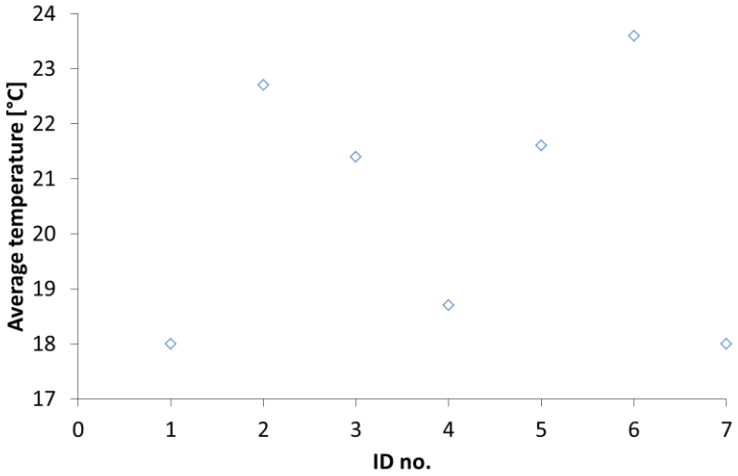


***Figure 24: Temperature inside the CT scanner.***

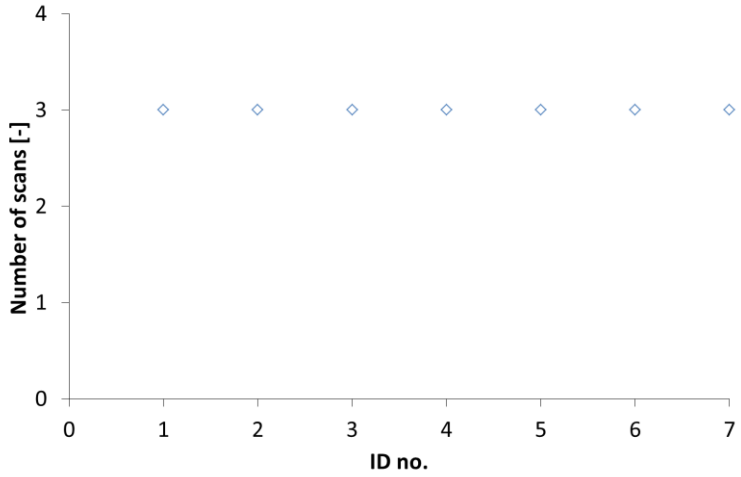


*Figure 25: Number of scans by participants.*

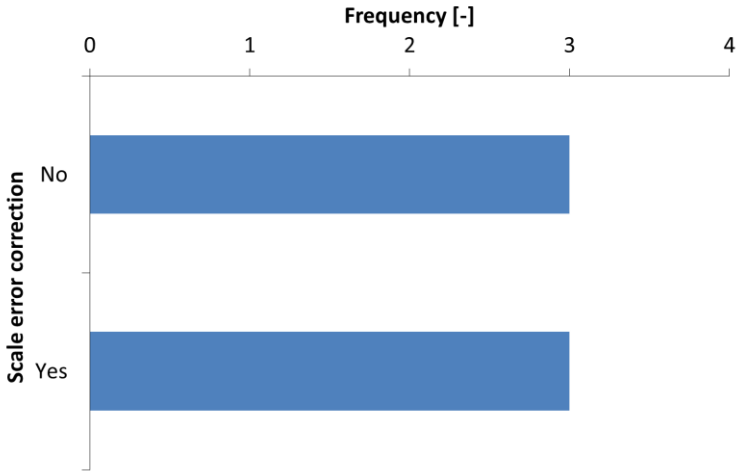


*Figure 26: Frequency of scale error correction.*

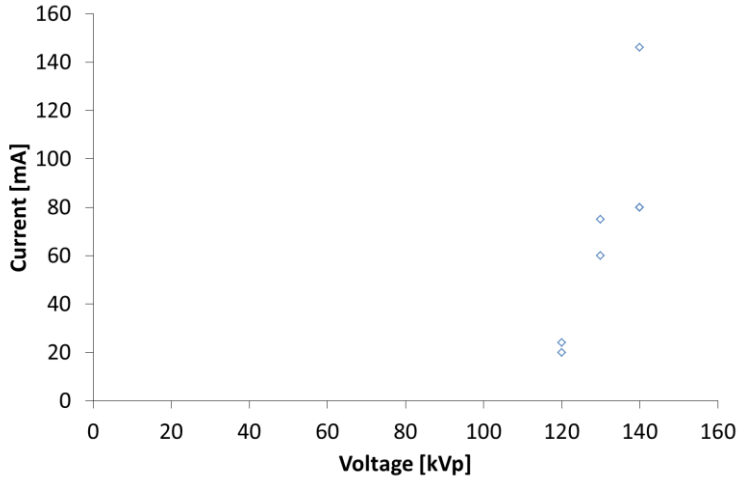


*Figure 27: Current vs. voltage.*

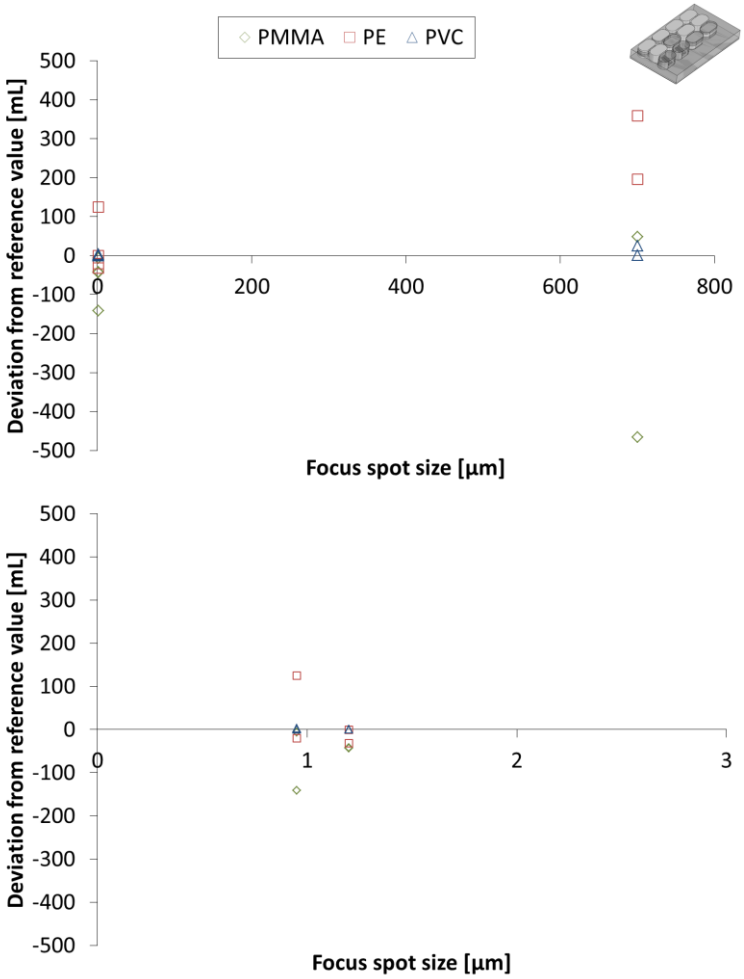


***Figure 28: Deviation from reference value vs. focus spot size for Phantom 1. Top: range 0 to 800 µm. Bottom: range 0 to 3 µm.***

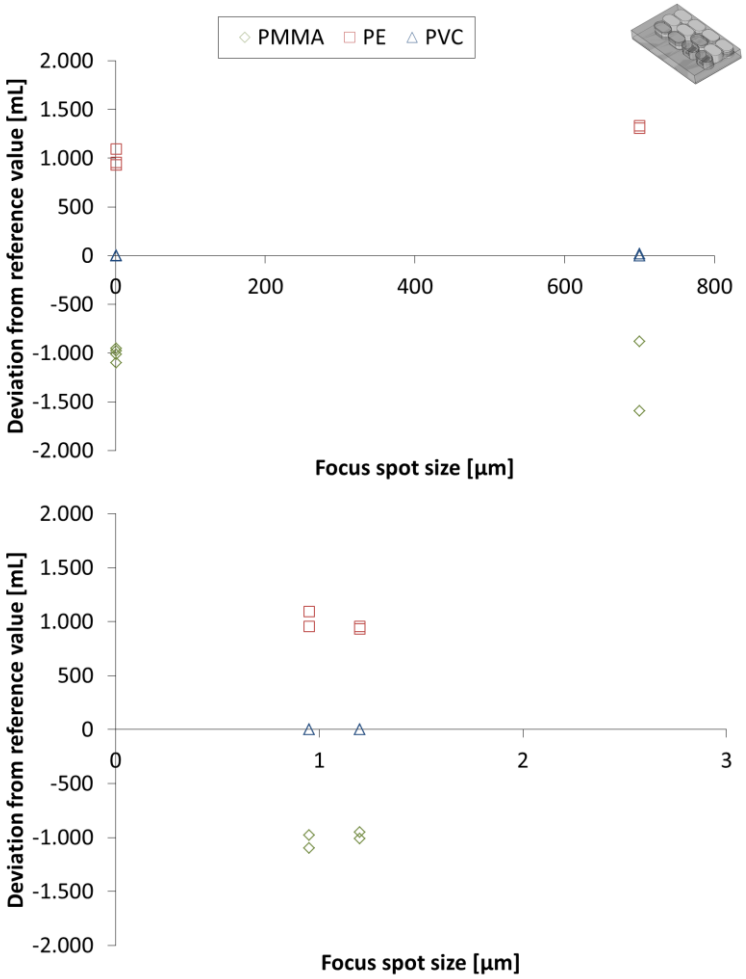


***Figure 29: Deviation from reference values vs. focus spot size for Phantom 2. Top: range 0 to 800 µm. Bottom: range 0 to 3 µm.***

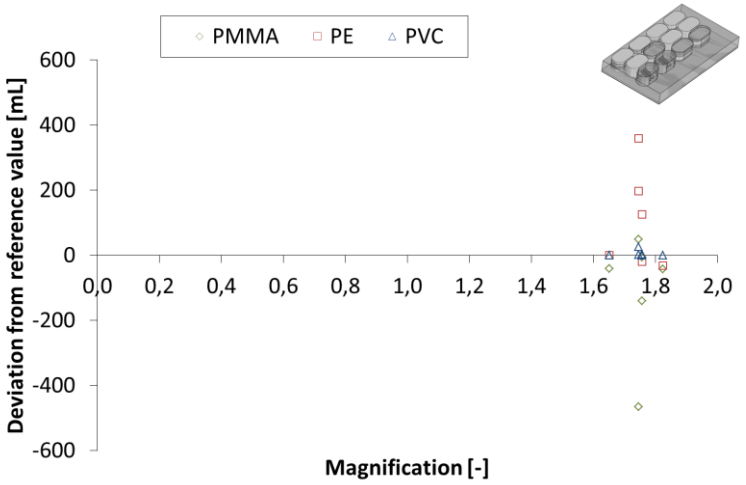


***Figure 30: Deviation from reference values vs. magnification for Phantom 1.***

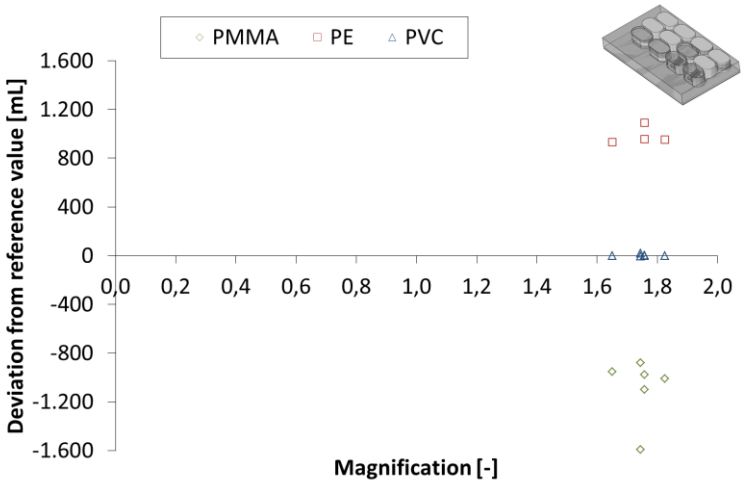


*Figure 31: Deviation from reference values vs. magnification for Phantom 2.*

*Table 8: Slice widths used by the participants.*

| ID no. | Slice width for phantoms [mm] |
|---|---|
| 1 | 10.0 |
| 2 | 1.0 |
| 3 | 2.0 |
| 4 | 3.0 |
| 5 | 10.0 |
| 6 | 1.0 |
| 7 | 10.0 |

| | |
|---|---|
| **MAX** | 10.0 |
| **AVG** | 5.3 |
| **MIN** | 1.0 |

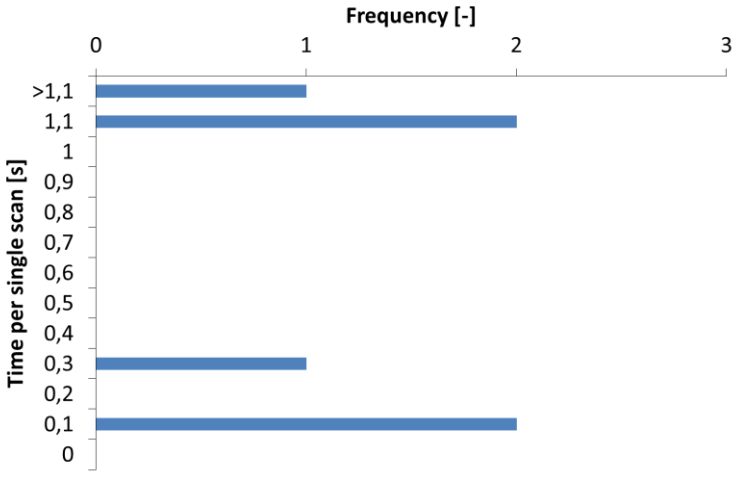


*Figure 32: Frequency of time per single scan.*

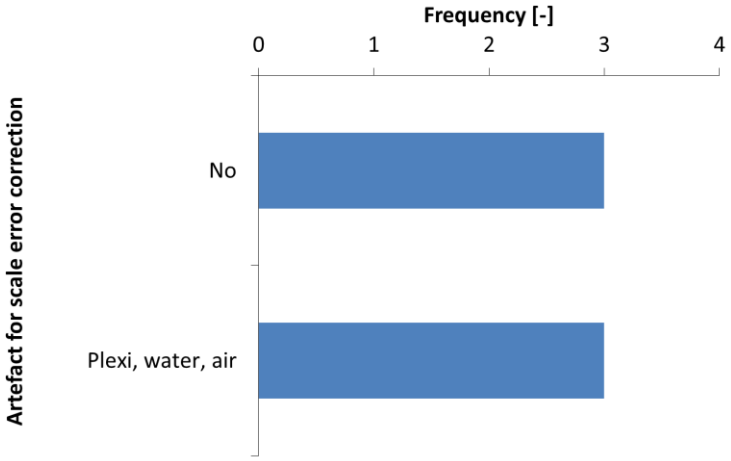


*Figure 33: Frequency of artefacts for scale error correction.*

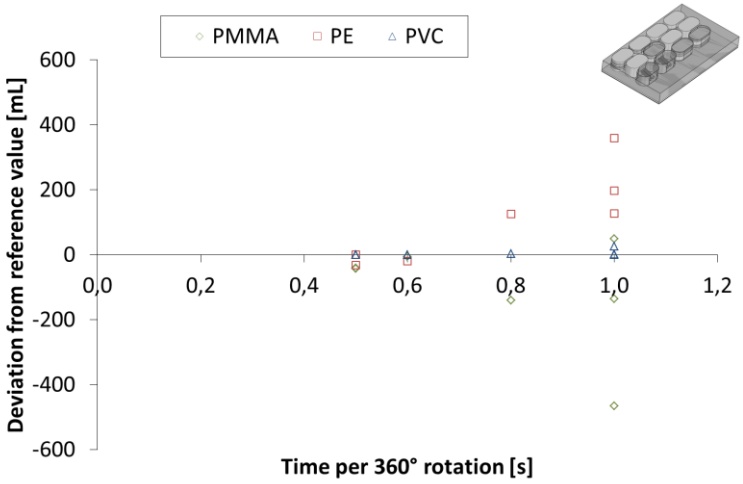


*Figure 34: Deviation from reference values vs. time per 360° rotation for Phantom 1.*

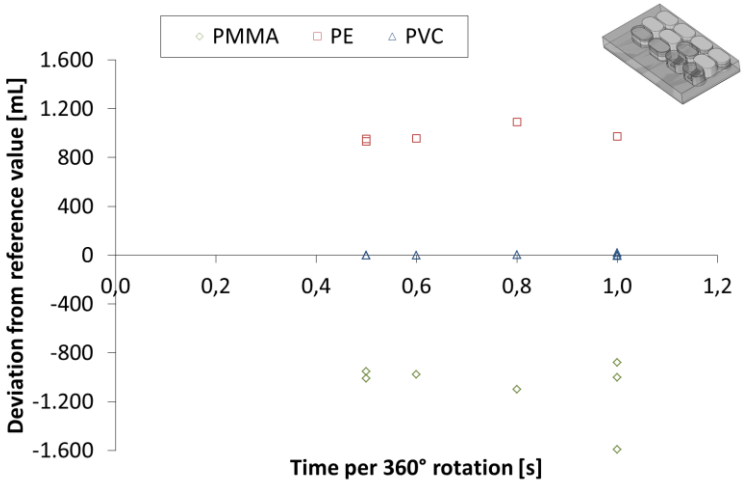


*Figure 35: Deviation from reference values vs. time per 360° rotation for Phantom 2.*

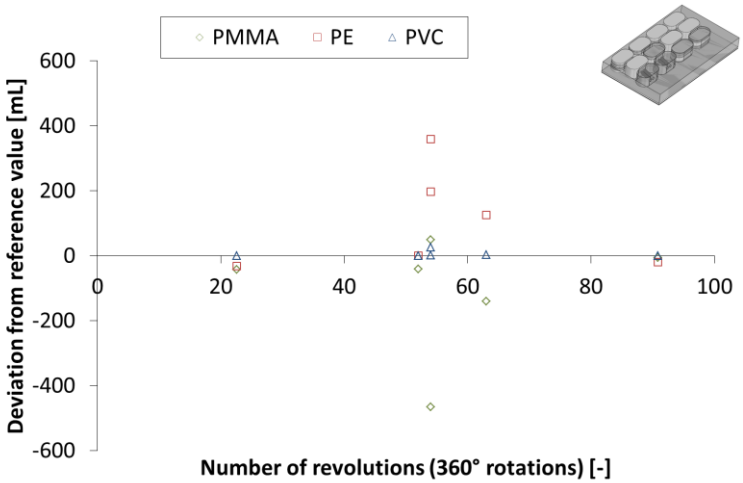


*Figure 36: Deviation from reference values vs. number of revolutions (360° rotations) for Phantom 1.*

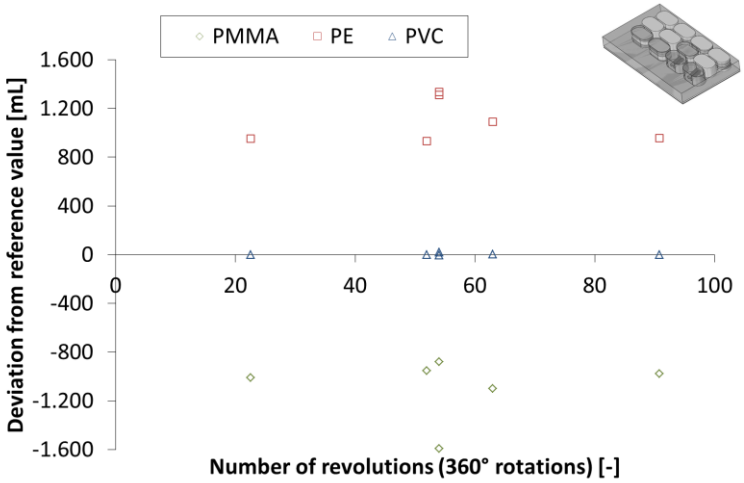


*Figure 37: Deviation from reference values vs. number of revolutions (360° rotations) for Phantom 2.*

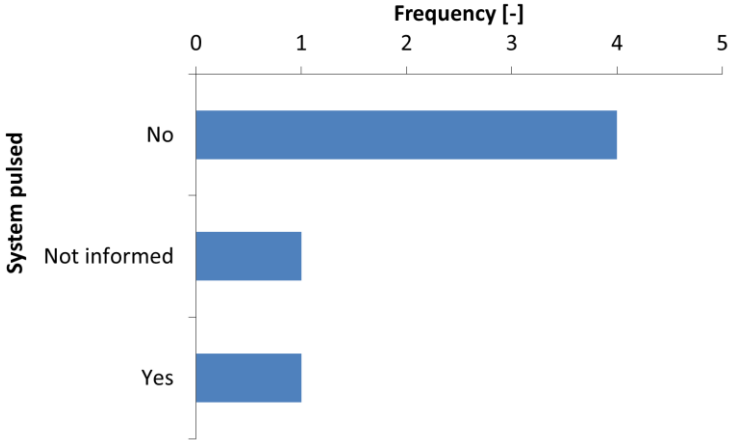


*Figure 38: Frequency of system pulsed.*

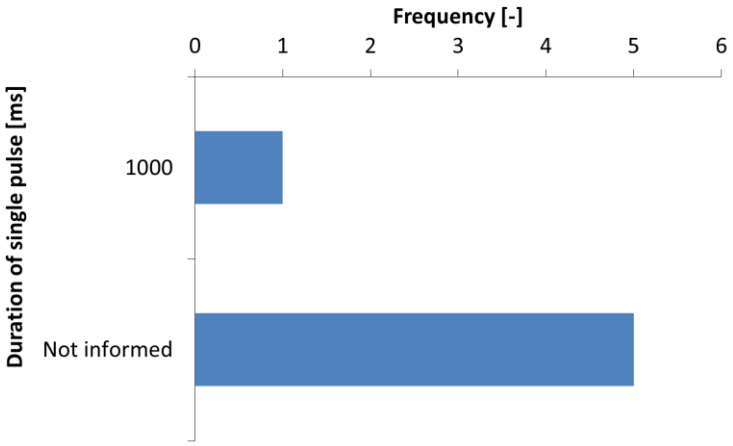


*Figure 39: Frequency of duration of single pulses.*

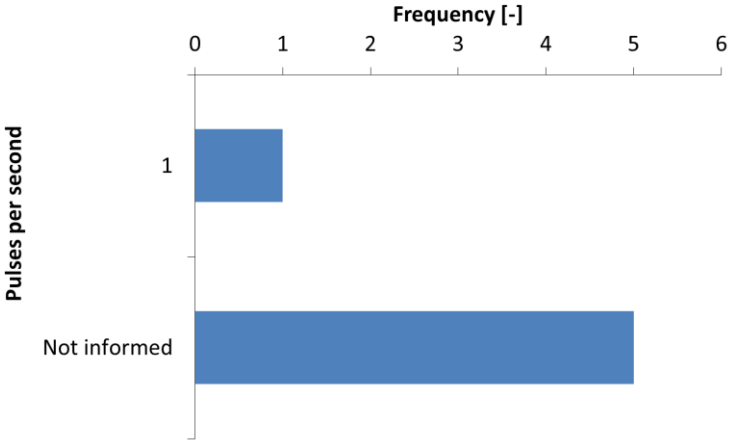


*Figure 40: Frequency of duration of pulses per second.*

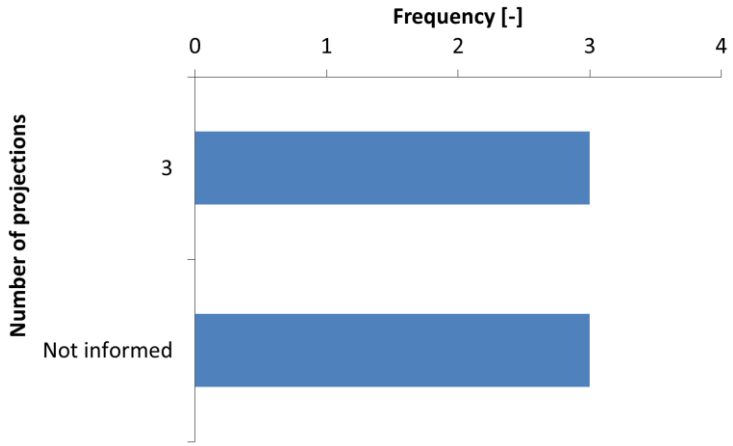


*Figure 41: Frequency of number of projections.*

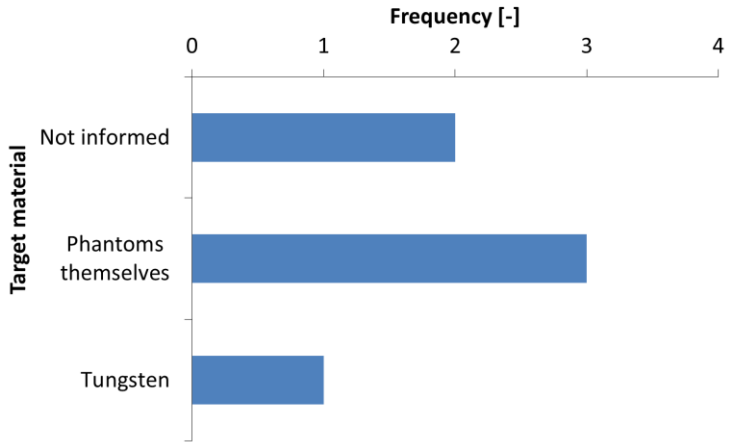


*Figure 42: Frequency of target material.*

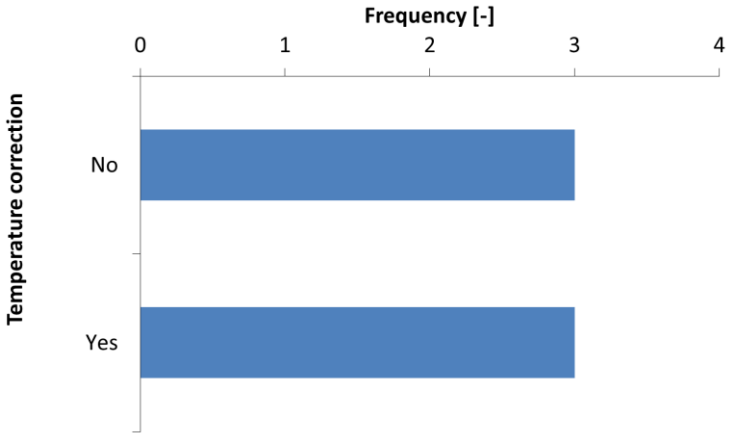


*Figure 43: Frequency of temperature correction.*

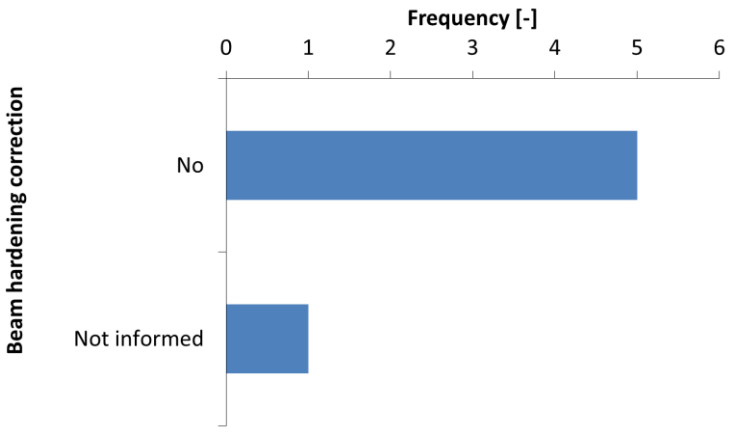


*Figure 44: Frequency of beam hardening correction.*

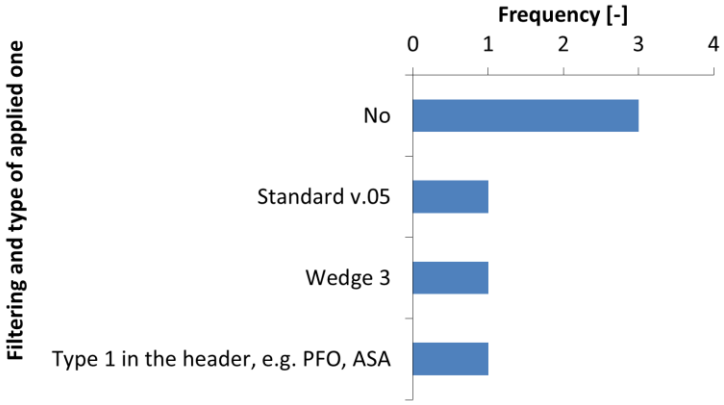


***Figure 45: Frequency of filtering and type of applied one.***

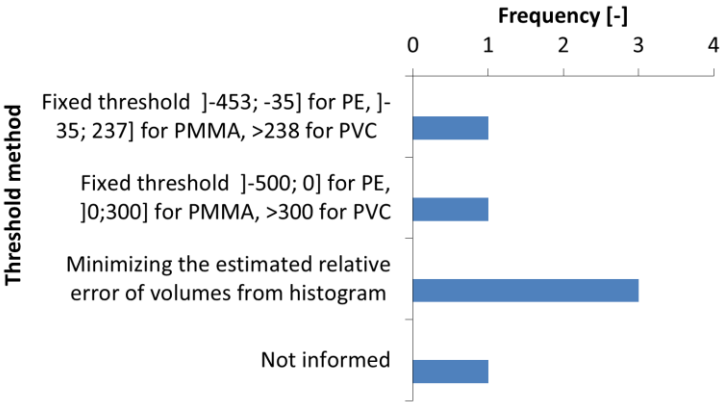


***Figure 46: Frequency of applied threshold method.***

## 4.8. Applied uncertainties by the participants

Only participant number 4 had stated an uncertainty using (4.3).

$$U = \frac{STD}{\sqrt{n}} \cdot k \qquad (k = 2) \tag{4.3}$$

Hence *STD* is the standard deviation, *n* is the number of replicated measurements, and *k* is the coverage factor.

## 4.9. Further information from the participants

In general the measuring procedures were followed by all participants without problems, but some detected problems and challenges were the following:

- The most participants did not have any experience of how to outline uncertainty budgets.
- The definition of some of the scanning and processing parameters was not obvious.
- Some participants had shifted around the location of the volume values for PMMA and PE in the measurement results for phantoms. This is corrected in the report by the coordinator.
- One of the participants discovered errors on their initial scans, and then these were replaced with new scans.

# 5. Conclusion

The main conclusions which were drawn from the project are summarized in the following.

- Circulation started in May 2011, and was completed in May 2012. 4 participants from 4 countries participated.
- Thanks to excellent support by all participants, the circulation was smooth and timely.
- All together, two synthetic phantoms representing real pig carcasses were circulated.
- Different volume measurands were considered, encompassing PMMA, PE, and PVC.
- Reference values for both phantoms were provided by DMRI and CGM using the principle of water displacement.
- Expanded measurement uncertainties obtained by CGM are in the range of 0-10 mL.
- The stability of the phantoms was documented through 3 reproduced measurements over a 4 month period on a clinical CT scanner under the same conditions at DMRI.
- Investigations confirmed that the mean variation between the three time periods were quite small, below 30 mL. ANOVA tests demonstrated that the reproduced measurements were not significant ($\alpha$=0.05), and the materials were stable enough.
- The measuring procedures were followed by all participants without problems.
- Six clinical CT scanners were involved.
- Results by the single participants were compared with the reference values provided by CGM.
- Each participant can use the comparison results in this report to investigate the presence of systematic errors and/or any underestimation of uncertainties.
- The most participants did not have any experience of how to outline uncertainty budgets. The expanded uncertainties stated by the participants are in the range 0-18 mL for both phantoms and all materials.
- Out of a total of 6 results obtained by the participants using CT scanning, 0% of the measurements yield $|E_n|$ values less than 1 and 100% larger than 1.
- More realistic uncertainties were estimated for the cases where $|E_n| \geq 1$, and values in the range 1-1090 mL were suggested.
- It was found that scale error correction particularly should be considered for ID no. 1 and 7 compared to the other IDs.
- The measured values by the participants seem to be overestimated or underestimated compared to the reference values. The reason to these trends could be due to the specified tolerances defined by the participants for segmentation of the polymer materials. The segmentation areas between the polymer materials compose of mixed pixel values, which make it difficult to evaluate which batch they should belong.
- Statistics of collected information concerning instrument settings and operator adjustments have shown that the participants in the comparison have followed state of the art procedures for their measurements,
- The phantoms are suitable artefacts for CT measurements of this kind.

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# 7. Appendix

Template
Selection of sealing boxes for the phantoms
Reference measurements
Density determination using pycnometers
Certificates and procedures
Calculation examples for reference measurements (for Phantom 1 only)
Summary of uncertainty budgets
Data for ANOVA tests

## 7.1. Template

| CIA-CT comparison | | |
|---|---|---|
| **Measurement report for Phantom** | | |
| Date | | |
| Participant | | |
| Reference person | | |
| CT scanner | | |
| Scan 1 | T_initial (°C) | |
| | T_final (°C) | |
| Scan 2 | T_initial (°C) | |
| | T_final (°C) | |
| Scan 3 | T_initial (°C) | |
| | T_final (°C) | |
| **Scanning parameters** | | |
| Helical scanning available (Yes/No) | | |
| Voltage (kVp) | | |
| Accelerating current (mA) | | |
| Slice width (mm) | | |
| Time per single scan (s) | | |
| Time per 360° rotation (s) | | |
| Number of revolutions (360° rotations) | | |
| System pulsed (Yes/No) | | |
| Duration of single pulse (ms) | | |
| Pulses per second | | |
| Magnification (X) | | |
| Source to detector distance (mm) | | |
| Source to object distance (mm) | | |
| Number of projections | | |
| Target material | | |
| Spot size (µm) | | |
| Others | | |
| **Processing parameters** | | |
| Scale correction (Y/N and indicate which reference item has been used) | | |
| Temperature correction (Y/N) | | |
| Software used for data processing and measurement (please indicate each software used and for which purpose) | | |
| Beam hardening correction (Y/N, which method was applied?) | | |
| Filtering (Y/N and which type of filter was applied?) | | |
| Threshold method (which method was applied?) | | |
| Uncertainty methods applied (please indicate which one was used) | | |
| Notes | | |

| Measurement results for Phantom | | | | | |
|---|---|---|---|---|---|
| | Scan 1 (mL) | Scan 2 (mL) | Scan 3 (mL) | Average (mL) | Expanded uncertainty (mL) |
| PMMA | | | | | |
| PE | | | | | |
| PVC | | | | | |
| Total | | | | | |

## 7.2. Selection of sealing boxes for the phantoms

Regarding to the circulation it was important to avoid damages and limit contamination of the phantoms. Different experiments were made to select the correct sealing box. An example of a sealing box is shown on Figure 47. It was in interest to investigate that the sealing and wrapping materials did not perform any noise on the scanned materials in a phantom. This phenomenon is due to the attenuation of the X-rays. The attenuation increases, when the geometrical thickness of the measuring object is increasing [Müller, 2010]. Additionally with constant energy and increasing atomic number, the maximum allowable penetration is decreasing [Kruth, 2010]. A test phantom, which was similar to the two used phantoms in the comparison, was used for the experiments with sealing and wrapping materials. Furthermore the significance of fixing the test phantom was investigated too with and without a rotation in proportion to how the test phantom was located on the table in the clinical CT scanner. For the calculations of the volumes of the scanned materials, software called PigClass was used [Christensen et al., 2010].

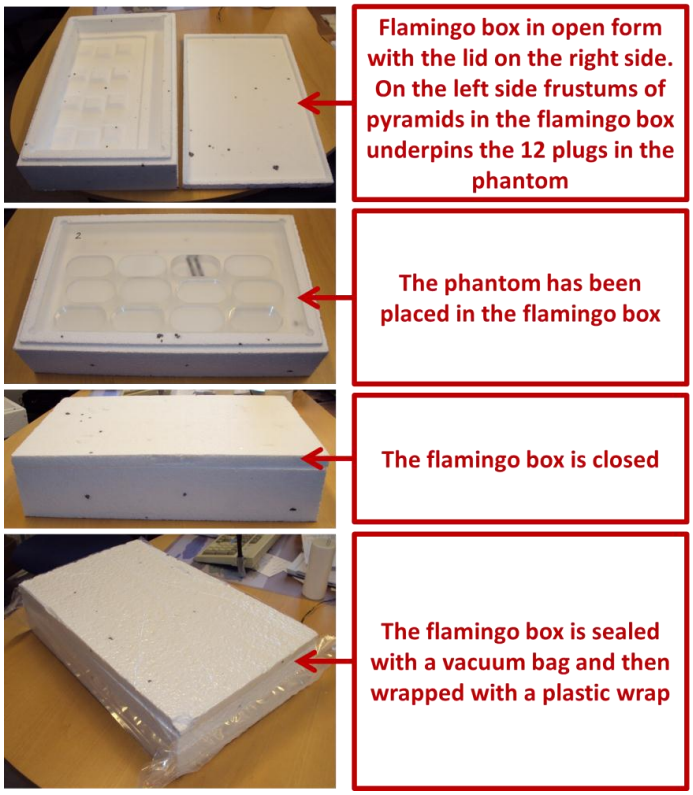



***Figure 47: Example of sealing box for one of the phantoms, acquired from DMRI.***

A Three-Factor Factorial Design was performed to investigate the selection of sealing materials. The experiments were performed with six repeated measurements. The three factors were specified at two-three levels to investigate the sealing, fixing and material effects on a test phantom, as presented in Table 9. The temperature during the experiments was approximately constant and was assumed to be neglected as influence parameter. An analysis of variance (ANOVA) was performed with regarding to the guidelines stated in [Montgomery, 2009]. The significance level approach was set to be $\alpha$=0.05. An experimental overview is shown in Table 10. All the scans were performed on a clinical CT scanner under the same conditions at Danish Meat Research Institute. The used scanning parameters are shown in Table 11. All scanning and setting parameters were the same for all the experiments. In Table 12 the densities are informed, and the

thermal expansion coefficient is indicated too for the materials which are relevant for the measurements. The statistical analysis was performed using Minitab. With regards to the stability investigation tests the residuals were evaluated for the test phantom. Residuals and model adequacy checking showed that the residuals failed the normality test for the test phantom, because of a small P value as shown in Figure 48. It means that data don't follow one of the assumptions of the regression. Some solutions to achieve a large P value are one or more of the following: (1) fit a different model, (2) weight the data differently or (3) exclude outliers. The author evaluated that there were too few data to delete eventual outliers. Instead it was assumed to try to neglect the two-factor and higher interactions, where these were implemented in the error for the DOE. This assumption did not improve the P value. The conclusion was that there was something wrong with the experiment and the ANOVA was not reliable. The main effect and interaction plots are shown in Figure 49. From these it was clear that the mean variation for the sealing and fixing methods were quite small, below 2 mL.

***Table 9: A Three-Factor Factorial Design (DOE).***

| **Factor** | **Level** | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Material | PMMA | PE | PVC |
| Sealing | Sealing | No sealing | |
| Fixing | Rotation | No rotation | |

***Table 10: Experimental plan.***

| **No.** | **Material** | **Sealing** | **Fixing** |
|---|---|---|---|
| 1 | PMMA | Sealing | Rotation |
| 2 | PMMA | Sealing | No rotation |
| 3 | PMMA | No sealing | Rotation |
| 4 | PMMA | No sealing | No rotation |
| 5 | PE | Sealing | Rotation |
| 6 | PE | Sealing | No rotation |
| 7 | PE | No sealing | Rotation |
| 8 | PE | No sealing | No rotation |
| 9 | PVC | Sealing | Rotation |
| 10 | PVC | Sealing | No rotation |
| 11 | PVC | No sealing | Rotation |
| 12 | PVC | No sealing | No rotation |

***Table 11: Scanning parameters.***

| **Parameter** | **Value** |
|---|---|
| Voltage in kV | 140 |
| Current In mA | 80 |
| Slice width in mm | 10 |
| Time per 360° rotation in s | 1 |
| Number of revolutions (360° rotation) | 54 |
| Source-detector distance in mm | 1099.3 |
| Source-object distance in mm | 630 |
| Target material | Tungsten |

*Table 12: Material characteristics.*

| Increasing density | Material | Density [kg/m$^3$] | Thermal expansion coefficient [$10^{-6}$ $K^{-1}$] |
|---|---|---|---|
| | Air at 20 °C and 101.325 kPa | 1.29 | Not relevant for the measurements |
| | Expanded polystyrene (used for fixture) | 16-640 | Not relevant for the measurements |
| | Low density Polyethylene (PE-LD) used as outer shell for wrapping and sealing | 910-925 | Not relevant for the measurements |
| | Polyethylene (PE) | 950 | 200 |
| | Mixture of Polyamide (PA) and Polyethylene (PE) used as vacuum bag for wrapping and sealing | 910-1150 | Not relevant for the measurements |
| | Water | 1000 | Not relevant for the measurements |
| | Poly methyl methacrylate (PMMA) | 1190 | 70 |
| | Polyvinyl chloride (PVC) | 1380 | 75 |

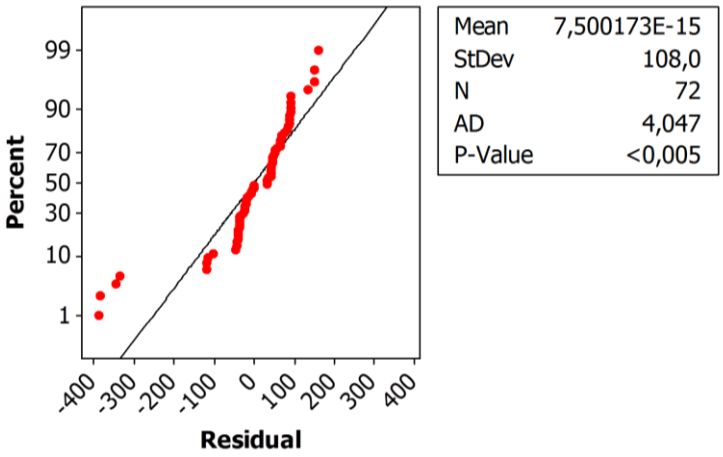



*Figure 48: Normal probability plot of residuals.*

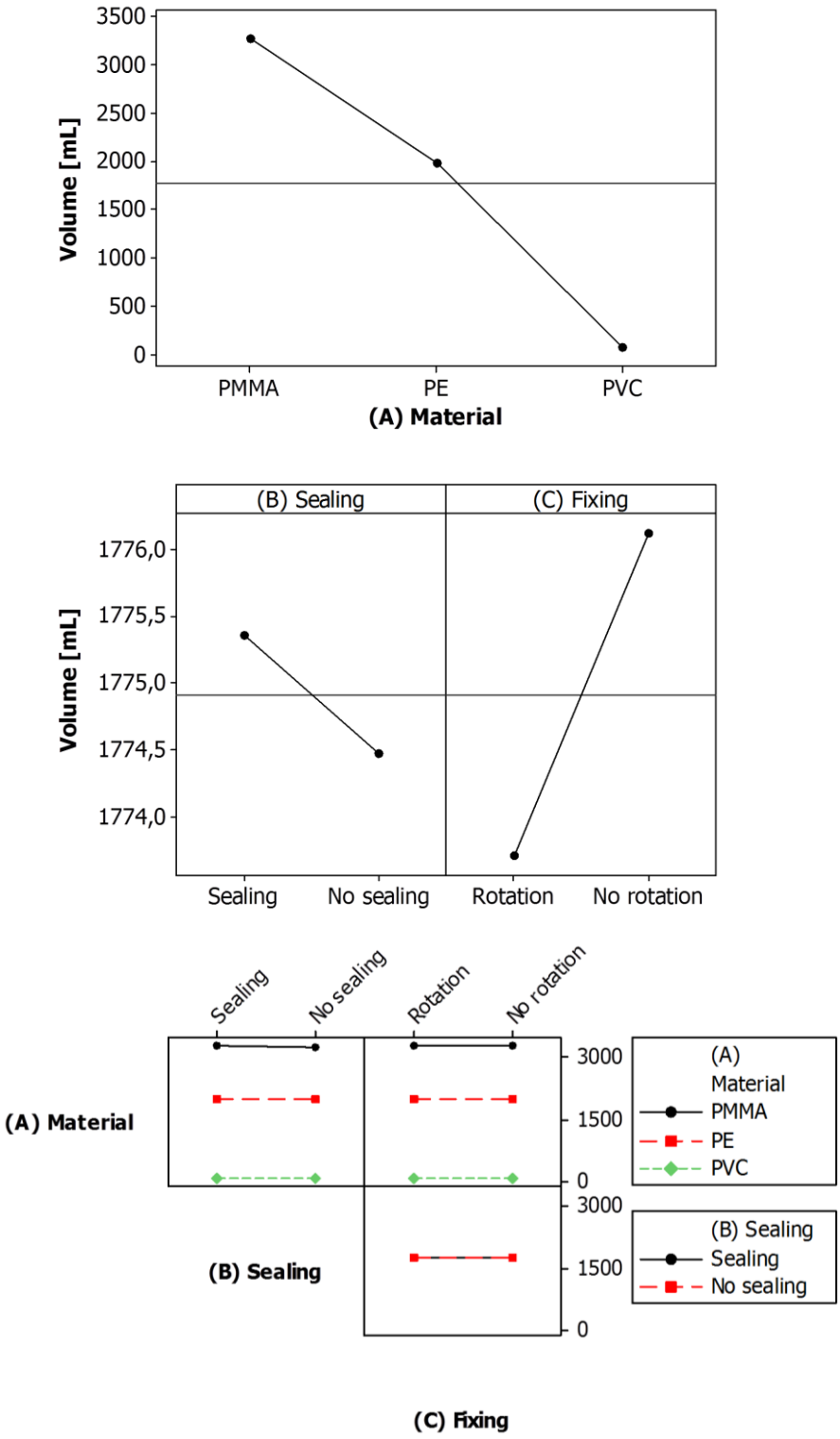



*Figure 49: Main effect and interaction plots. Volume in mL.*

## 7.3. Reference measurements

Two synthetic phantoms were used instead of real pig carcasses for circulation: a skinny pig carcass (Phantom 1, see Figure 50) and a fat pig carcass (Phantom 2, see Figure 51) with a higher content of fat (PE). Two different investigations were performed for the two phantoms. The performed investigations were repeatability and stability of the phantoms. The repeatability refers to measurements without moving the measured part.

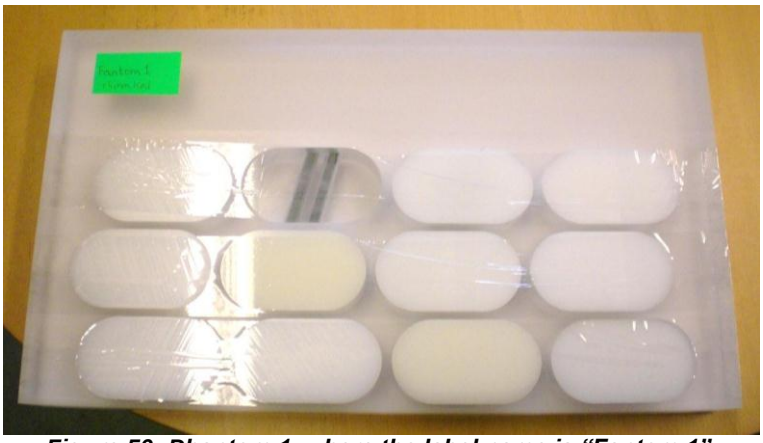


***Figure 50: Phantom 1, where the label name is "Fantom 1".***

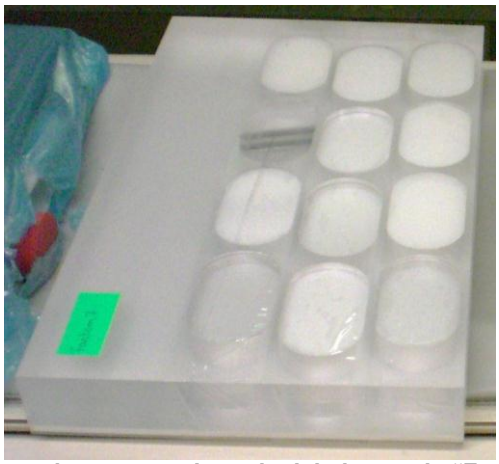


***Figure 51: Phantom 2, where the label name is "Fantom 7".***

The reference values were performed before the circulation and carried out in March 2011. Reference volumes were determined by water displacement through a method of finding the absolute density [DIN EN 725-7, 1996] [Appendix 7.4]. The equipment used at DMRI to perform the reference values was a thermometer, a pycnometer, a weight and a barometer. Six reversal measurement and transfer of traceability by comparator measurements were carried out. These values were not verified by new measurements, because it is a very unstable process, when disassemble and assemble the phantoms again. Instead the stability of the phantoms was documented through 3 reproduced measurements over a 4 month period (November 2011, December 2011 and February 2012) on a clinical CT scanner under the same conditions at DMRI. For computing volumes of the contents of PMMA, PE and PVC in the phantoms, commercial software (PigClass) was used [Christensen et al., 2010].

### 7.3.1. Measuring uncertainty

A practical approach inspired by [ISO 14253-2, 2011] was used for uncertainty estimation, as a simplification of the GUM approach [ISO/IEC Guide 98-3, 2008]. The considered uncertainty contributes were the following: measuring weights $u_r$, water absorption for artefact $u_a$, technical weight $u_w$, temperature effects $u_t$, and reproducibility due to the measurement process $u_p$. The temperature effects were divided in three sub contributions, which involved the components coming from temperature difference for instrument $u_{t1}$, difference for artefact $u_{t2}$, and deviation from the standard reference temperature $u_{t3}$. The models in (7.1) and (7.2) are used for uncertainty estimation.

$$U = k \cdot u_c \qquad (k = 2) \tag{7.1}$$

Here, $U$ is the expanded uncertainty, $u_c$ is the combined standard uncertainty and $k$ is the coverage factor ($k=2$ for a coverage probability of 95 %). The considered uncertainty contributors are given in (7.2).

$$U = k \cdot \sqrt{u_r{}^2 + u_w{}^2 + u_{t1}{}^2 + u_{t2}{}^2 + u_{t3}{}^2 + u_p{}^2 + u_a{}^2} \tag{7.2}$$

The distribution of uncertainty contributions are summarized in Figure 52 for Phantom 1 and Figure 53 for Phantom 2. It is clear that the uncertainty component is greatest for water absorption in the case of PMMA compared to PE and PVC – maybe because of that PMMA absorphs humidity (and water), when PE and PVC are resistant to humidity and water [Jensen et al., 2005].

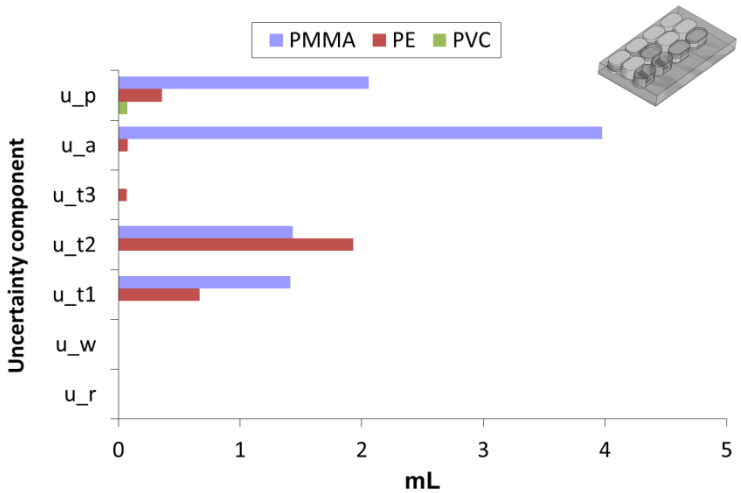



*Figure 52: Phantom 1 – Distribution of uncertainty contributions. All values are in mL.*

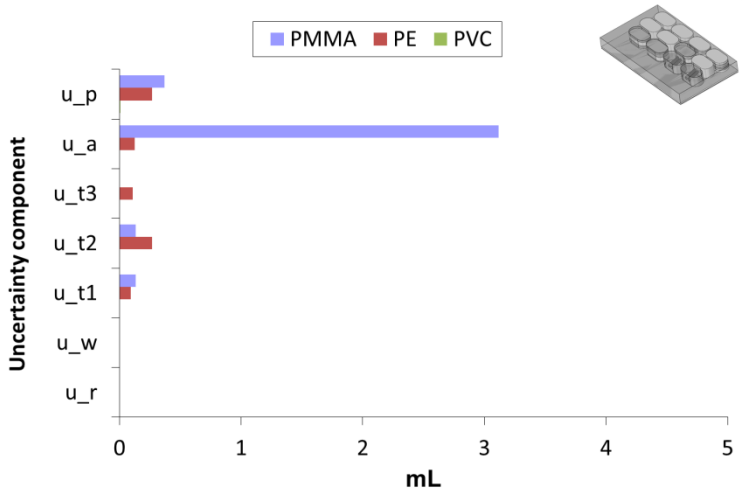



*Figure 53: Phantom 2 – Distribution of uncertainty contributions. All values are in mL.*

The graph, which shows the variation of the reference measurements, can be used to evaluate repeatability and consistency of measurements [De Chiffre et al., 2004]. An example of the measurements of Phantom 1 before the circulation is given in Figure 54, and for Phantom 2 in Figure 55. The deviation of each measurement was based on the deviation between the measured value and the average value of the six measurements. Hence the reversal measurements show a maximum deviation of 2.3 mL for PMMA for Phantom 1. For Phantom 2 the maximum deviation was 0.5 mL for PMMA. It can be seen that the variation is greatest for PMMA compared to PE and PVC – maybe because of the bigger contents of PMMA. Note that PMMA absorphs humidity (and water), when PE and PVC are resistant to humidity and water [Jensen et al., 2005], which can influence on the results too. The calculated reference values and their corresponding uncertainties are shown in Table 13 (for calculation examples, see Calculation examples for reference measurements).

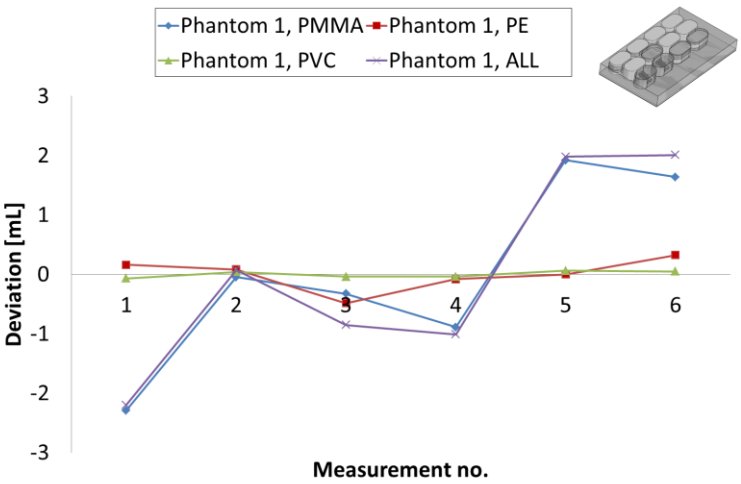



*Figure 54: Phantom 1 – Variation of six reversal measurements before the circulation.*

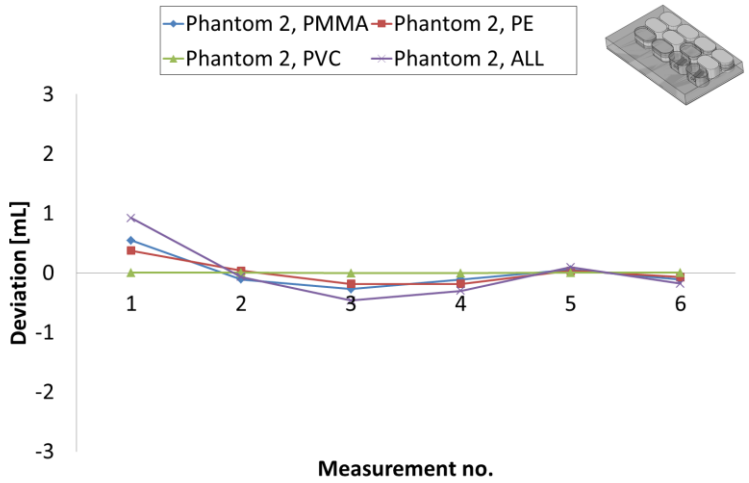



*Figure 55: Phantom 2 – Variation of six reversal measurements before the circulation.*

*Table 13: Phantoms – Reference values and their corresponding expanded uncertainties (k=2). Values are in mL.*

| | PMMA | | PE | | PVC | |
|---|---|---|---|---|---|---|
| Phantom no. | Y | U | Y | U | Y | U |
| 1 | 3896.8 | 9.8 | 1275.8 | 4.1 | 7.8 | 0.1 |
| 2 | 3055.3 | 6.3 | 2118.3 | 0.9 | 7.7 | 0.0 |

### 7.3.2. Stability investigation

Some polymer materials changes through time [Bauer et al., 2005]. Traditionally it is recommended checking the stability of the phantoms through re-calibrations after the circulation using the same method as for the reference measurements. But DMRI demanded that the sealed and wrapped phantoms should not be unwrapped. Therefore the same calibration method as for the reference measurements was not performed. Instead a stability investigation was performed using several scans through time on the same clinical CT scanner under the same conditions at DMRI. For the calculations of the volumes, software called PigClass was used [Christensen et al., 2010]. In PigClass the initial thresholds between the different materials were indicated (-150, 0 and 160 HU) based on experiences from DMRI. But PigClass software did not compensate for systematic error due to the temperature and these were performed manually.

A Two-Factor Factorial Design was performed to investigate the relationship between material type and period of time. The experiments were performed with nine repeated measurements. The two factors were specified at three levels to investigate the time and material effects on the phantoms, as presented in Table 14. The three material types were PMMA, PE and PVC. The three tested periods of time were November 2011, December 2011 and February 2012. An analysis of variance (ANOVA) for the material types and period of times on the phantoms was performed with regarding to the guidelines stated in [Montgomery, 2009]. The significance level approach was set to be $\alpha$=0.05. An experimental overview is shown in Table 15. The used scanning parameters were similar to the one in the sealing tests. The statistical analysis was performed using Minitab. With regards to the stability investigation tests the residuals were evaluated for both phantoms. Residuals and model adequacy checking showed that the residuals failed the normality test for Phantom 1, because of a small P value as shown in Figure 56. It means that data don't follow one of the assumptions of the regression. Some solutions to achieve a large P value are one or more of the following: (1) fit a different model, (2) weight the data differently or (3) exclude outliers. The

author evaluated that there were too few data to delete eventual outliers. Instead it was assumed to neglect the two-factor interactions, where these were implemented in the error for the DOE. This assumption gave a higher P value as shown in Figure 57. The main effect and interaction plots are shown in Figure 58. Similar results were obtained for Phantom 2, see Figure 59, Figure 60 and Figure 61. From these it was clear that the mean variation between the three time periods were quite small, below 30 mL. Based on the ANOVAs in Table 16 and Table 17 it was evaluated that the used materials were stable.

***Table 14: A Three-Factor Factorial Design (DOE).***

| Factor | Level | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Material | PMMA | PE | PVC |
| Sealing | Sealing | No sealing | |
| Fixing | Rotation | No rotation | |

***Table 15: Experimental plan.***

| No. | Material | Sealing | Fixing |
|---|---|---|---|
| **1** | PMMA | Sealing | Rotation |
| **2** | PMMA | Sealing | No rotation |
| **3** | PMMA | No sealing | Rotation |
| **4** | PMMA | No sealing | No rotation |
| **5** | PE | Sealing | Rotation |
| **6** | PE | Sealing | No rotation |
| **7** | PE | No sealing | Rotation |
| **8** | PE | No sealing | No rotation |
| **9** | PVC | Sealing | Rotation |
| **10** | PVC | Sealing | No rotation |
| **11** | PVC | No sealing | Rotation |
| **12** | PVC | No sealing | No rotation |

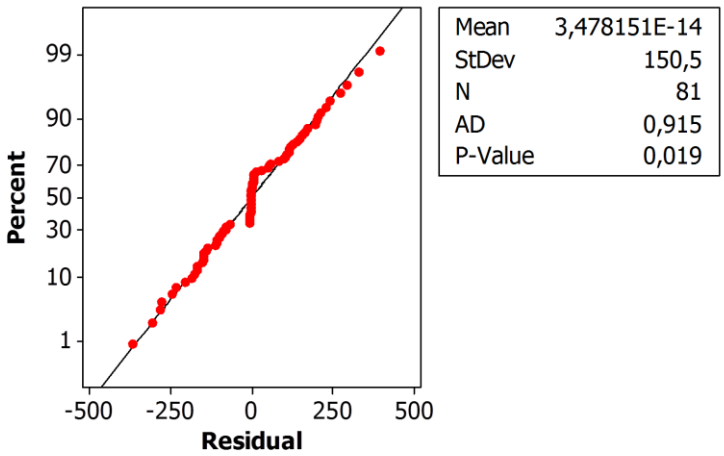



***Figure 56: Phantom 1 – Normal probability plot of residuals (including interaction AB).***

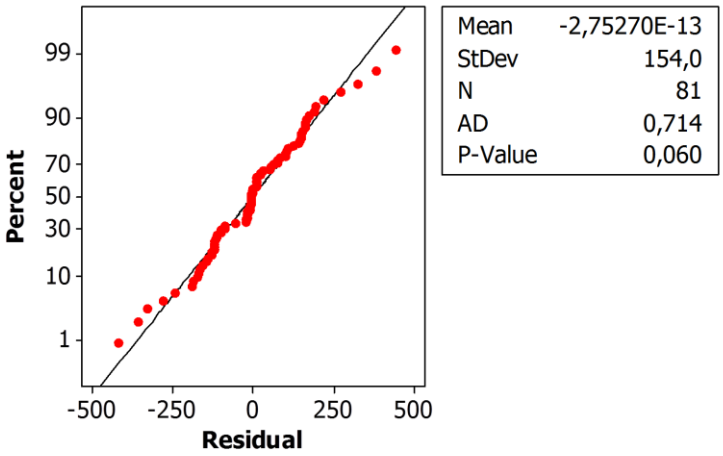



***Figure 57: Phantom 1 – Normal probability plot of residuals (excluding interaction AB).***

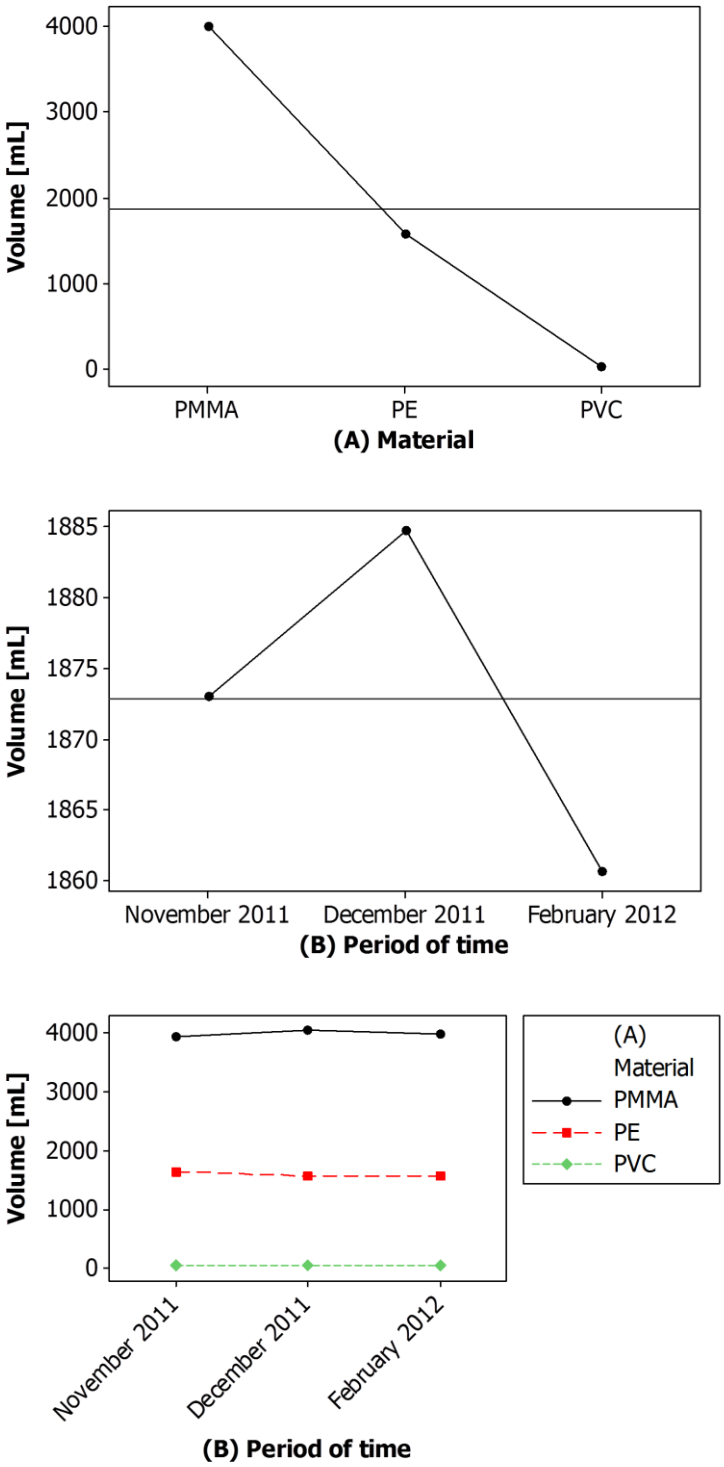



*Figure 58: Phantom 1 – Main effect and interaction plots.*

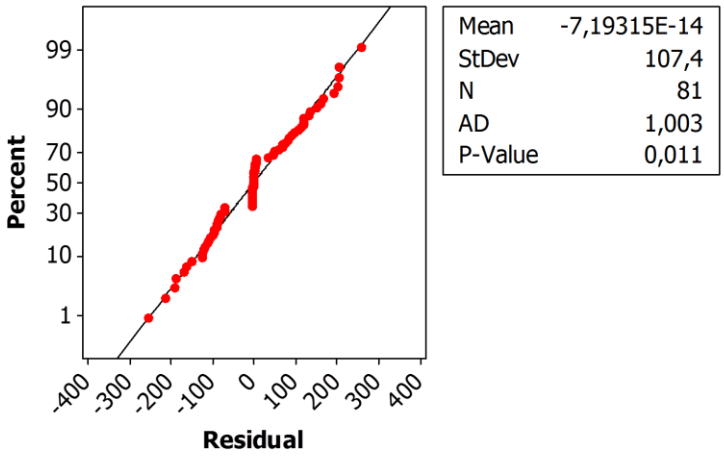



*Figure 59: Phantom 2 – Normal probability plot of residuals (including interaction AB).*

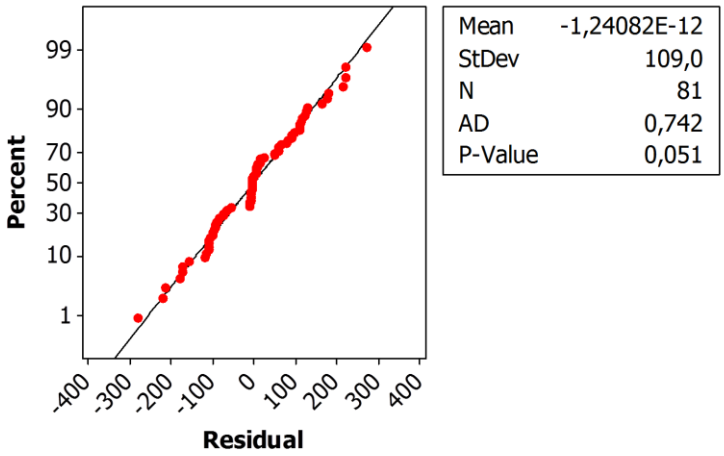



*Figure 60: Phantom 2 – Normal probability plot of residuals (excluding interaction AB).*

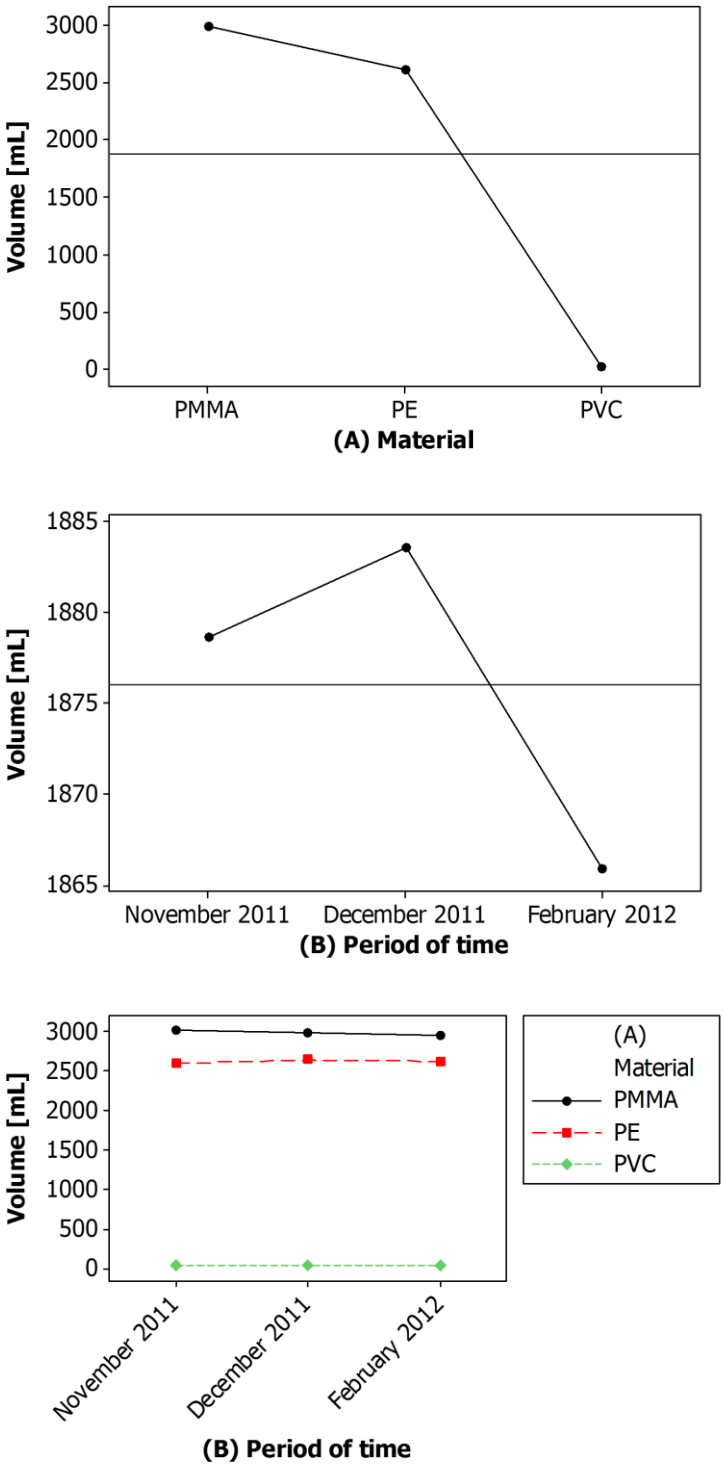



*Figure 61: Phantom 2 – Main effect and interaction plots.*

*Table 16: Phantom 1 – Analysis of variance for the volume of materials.*

| Source of variation | SS | df | MS | F-value | P-value |
|---|---|---|---|---|---|
| **Material (A) at three levels (PMMA. PE and PVC)** | 215496285 | 2 | 107748142 | 4317.27 | 0.000 |
| **Period of time (B) at three levels (November 2011. December 2011 and February 2012)** | 7813 | 2 | 3906 | 0.16 | 0.855 |
| **Error** | 1896766 | 76 | 24957 | | |
| **Total** | 217400863 | 80 | | | |

*Table 17: Phantom 2 – Analysis of variance for the volume of materials.*

| Source of variation | SS | df | MS | F-value | P-value |
|---|---|---|---|---|---|
| **Material (A) at three levels (PMMA. PE and PVC)** | 140103757 | 2 | 70051879 | 5598.20 | 0.00 |
| **Period of time (B) at three levels (November 2011. December 2011 and February 2012)** | 4497 | 2 | 2248 | 0.18 | 0.836 |
| **Error** | 951010 | 72 | 12513 | | |
| **Total** | 141059264 | 80 | | | |

## 7.4. Density determination using pycnometers

Generally the volume expansion can be found of (7.3) [Young, 2004] and (7.4) [Nordling, 2004].

$$\Delta V = \beta \cdot V_0 \cdot \Delta T \tag{7.3}$$

Hence $\Delta V$ is the volume expansion difference, $\beta$ is the volumetric expansion coefficient, $V_0$ is the original volume and $\Delta T$ is the temperature difference.

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p \tag{7.4}$$

Hence $V$ is the volume, $\partial V$ is the volumetric change, $\partial T$ is temperature change and $p$ is the pressure. The relation between the linear expansion coefficient (normally used) and the volumetric expansion coefficient can we written as given in (7.5) [Young, 2004].

$$\beta = 3 \cdot \alpha \tag{7.5}$$

Hence $\alpha$ is the linear expansion coefficient. Note that the thermal expansion coefficient of water increases with increasing temperature in the used application range for the experiments. But the volume decreases with increasing temperature for water in the application rang of 0 °C and 4 °C [Young, 2004]. The measurement procedure and strategy is made as follows in [Sartorius, 1999], where a fully description is given; first the weight of the pycnometer together with inserted object ($m_0$ + $m_S$) has to be measured. Then water should be added and the weight $m'_{H2O}$ has to be determined (measured weight minus $m_0$ + $m_S$). The volume of added water $V'_{H2O}$ can be obtained as given in (7.6).

$$V'_{H_2O} = \frac{m'_{H_2O}}{\rho_{H_2O}} \tag{7.6}$$

The volume of the measured solid object $V_s$ is found as the difference between the volume of water that fills the empty pycnometer V and the volume $V'_{H2O}$, so

$$V_S = V - V'_{H_2O} = \frac{m_{H_2O} - m'_{H_2O}}{\rho_{H_2O}} \tag{7.7}$$

Then the density of measured object $\rho_S$ can be determined as

$$\rho_S = \frac{m_S}{V_S} = \frac{m_S \cdot \rho_{H_2O}}{m_{H_2O} - m'_{H_2O}} = \frac{m_S \cdot \rho_{H_2O}}{m_{H_2O} - m_0 + m_S} \tag{7.8}$$

The density of water varies depending on the ambient temperature and pressure with reference to NMKL procedure no 13 (2002) [Appendix 7.5], which should be taken in consideration, where the

density of water can be determined based on the conversion factor *Z* (see NMKL procedure no. 13) as given in (7.9).

$$\rho_{H_2O} = Z^{-1} \tag{7.9}$$

The density of a substance at temperature $T_2$ can be calculated with the aid of the temperature $T_1$ and the volume expansion coefficient, so

$$\rho_2 = \frac{\rho_1}{1+\beta\cdot(T_2 - T_1)} \tag{7.10}$$

The important parameters, which should be noted for the volume calibration, are:

- A pycnometer is used for determination of specific gravity weight per unit volume of the used liquid (distil water[1]).
- A weight is used for weighting of the measured objects.
- A thermometer is used to consider the thermal expansion during the experiments.
- A barometer is used for determination of the atmospheric pressure.

Note that the influence of surface tension from distil water is assumed to be neglected. Furthermore the buoyancy correction should not be made, since the used weight correct for it itself. Fundamental information of buoyancy, pressure and fluids can be found in [Young, 2004].

[1] Note that the linear thermal expansion coefficient for water is $69 \times 10^{-6}$ $K^{-1}$.

## 7.5. Certificates and procedures

**NMKL PROCEDURE**
**NR. 13 (2002)**

Volumetrisk kontrol

Side: 13 af 19
Version: 1
Dato: 10.06.03
Godkendt: Ole Bjørn Jensen

**4.6.3 Konverteringsfaktoren Z (µl/mg), som funktion af temperatur og lufttryk, for destilleret vand** (ISO 8655-6: 2002)

| Temperatur °C | Lufttryk mbar | | | | | |
|---|---|---|---|---|---|---|
| | 800 | 853 | 907 | 960 | 1013 | 1067 |
| 15 | 1.0018 | 1.0018 | 1.0019 | 1.0019 | 1.0020 | 1.0020 |
| 15.5 | 1.0018 | 1.0019 | 1.0019 | 1.0020 | 1.0020 | 1.0021 |
| 16 | 1.0019 | 1.0020 | 1.0020 | 1.0021 | 1.0021 | 1.0022 |
| 16.5 | 1.0020 | 1.0020 | 1.0021 | 1.0022 | 1.0022 | 1.0023 |
| 17 | 1.0021 | 1.002 1 | 1.0022 | 1.0022 | 1.0023 | 1.0023 |
| 17.5 | 1.0022 | 1.0022 | 1.0023 | 1.0023 | 1.0024 | 1.0024 |
| 18 | 1.0022 | 1.0023 | 1.0024 | 1.0024 | 1.0025 | 1.0025 |
| 18.5 | 1.0023 | 1.0024 | 1.0025 | 1.0025 | 1.0026 | 1.0026 |
| 19 | 1.0024 | 1.0025 | 1.0025 | 1.0026 | 1.0027 | 1.0027 |
| 19.5 | 1.0025 | 1.0026 | 1.0026 | 1.0027 | 1.0028 | 1.0028 |
| 20 | 1.0026 | 1.0027 | 1.0027 | 1.0028 | 1.0029 | 1.0029 |
| 20.5 | 1.0027 | 1.0028 | 1.0028 | 1.0029 | 1.0030 | 1.0020 |
| 21 | 1.0028 | 1.0029 | 1.0030 | 1.0030 | 1.0031 | 1.0031 |
| 21.5 | 1.0030 | 1.0030 | 1.0031 | 1.0031 | 1.0032 | 1.0032 |
| 22 | 1.0031 | 1.0031 | 1.0032 | 1.0032 | 1.0033 | 1.0033 |
| 22.5 | 1.0032 | 1.0032 | 1.0033 | 1.0033 | 1.0034 | 1.0035 |
| 23 | 1.0033 | 1.0033 | 1.0034 | 1.0035 | 1.0035 | 1.0036 |
| 23.5 | 1.0034 | 1.0035 | 1.0035 | 1.0036 | 1.0036 | 1.0037 |
| 24 | 1.0035 | 1.0036 | 1.0036 | 1.0037 | 1.0038 | 1.0033 |
| 24.5 | 1.0037 | 1.0037 | 1.0038 | 1.0038 | 1.0039 | 1.0039 |
| 25 | 1.0033 | 1.0038 | 1.0039 | 1.0039 | 1.0040 | 1.0041 |
| 25.5 | 1.0039 | 1.0040 | 1.0040 | 1.0041 | 1.0041 | 1.0042 |
| 26 | 1.0040 | 1.0041 | 1.0042 | 1.0042 | 1.0043 | 1.0043 |
| 26.5 | 1.0042 | 1.0042 | 1.0043 | 1.0043 | 1.0044 | 1.0045 |
| 27 | 1.0043 | 1.0044 | 1.0044 | 1.0045 | 1.0045 | 1.0046 |
| 27.5 | 1.0044 | 1.0045 | 1.0046 | 1.0046 | 1.0047 | 1.0047 |
| 28 | 1.0046 | 1.0046 | 1.0047 | 1.0048 | 1.0048 | 1.0049 |
| 28.5 | 1.0047 | 1.0048 | 1.0048 | 1.0049 | 1.0050 | 1.0050 |
| 29 | 1.0049 | 1.0049 | 1.0050 | 1.0050 | 1.0051 | 1.0052 |
| 29.5 | 1.0050 | 1.005 1 | 1.0051 | 1.0052 | 1.0052 | 1.0053 |
| 30 | 1.0052 | 1.0052 | 1.0053 | 1.0053 | 1.0054 | 1.0055 |

DANAK
CAL Reg. nr. 9

# Kalibreringscertifikat

FORCE TECHNOLOGY

| | |
|---|---|
| **Certifikatnummer** | 9.11-44-1038. |
| **Certifikatet udskrevet** | 2011-03-16. |
| **Side** | 1 af 3 |
| **Rekvirent** | TI-DMRI<br>Maglegårdsvej 2<br>4000 Roskilde.<br>Attention: Kirsten Jensen.<br>- |
| **Kalibreringssted** | TI-DMRI<br>Maglegårdsvej 2<br>4000 Roskilde.<br>lokale: D267. |
| **Kundeudstyr** | Teknisk vægt. |
| **Fabrikat** | Sartorius. |
| **Typebetegnelse** | BP 3100 S. |
| **Fabrikationsnummer** | 70903749. |
| **Internt nummer** | SF 70671. |
| **Maximumslast** | 3100 g. |
| **Delingsværdi** | 0,01 g. |
| **Kalibreringsresultat** | Se side 2. |
| **Kalibreret af** | Erling Henriksen. |
| **Kalibreringsdato** | 2011-03-15. |
| **Instruktion** | Kalibreringen er udført som beskrevet i FORCE Instruktion nr. 9.11-02.B01. |
| **Anvendt udstyr** | Massenormalers nummer/klasse: X01003/F1<br><br>Termometer: A70176. Barometer: A75018. |
| **Bemærkninger** | -<br>-<br>-<br>- |
| **Underskrevet den** | 2011-03-29 |
| **Underskrifter** | Erling Henriksen.<br>Underskriftberettiget. |

**FORCE Technology.**
Navervej 1 6600 Vejen Tlf.: 76 96 16 00 Fax.: 75 36 41 55 epostkasse: vejning@force.dk

## Kalibreringsresultater - opvejning

FORCE TECHNOLOGY

| | | | |
|---|---|---|---|
| **Certifikatnummer** | 9.11-44-1038. | **Lufttemperatur** | 20,6° Celcius |
| **Side** | 2 af 3 | **Barometerstand** | 1023,3 hPascal |
| | | | - |

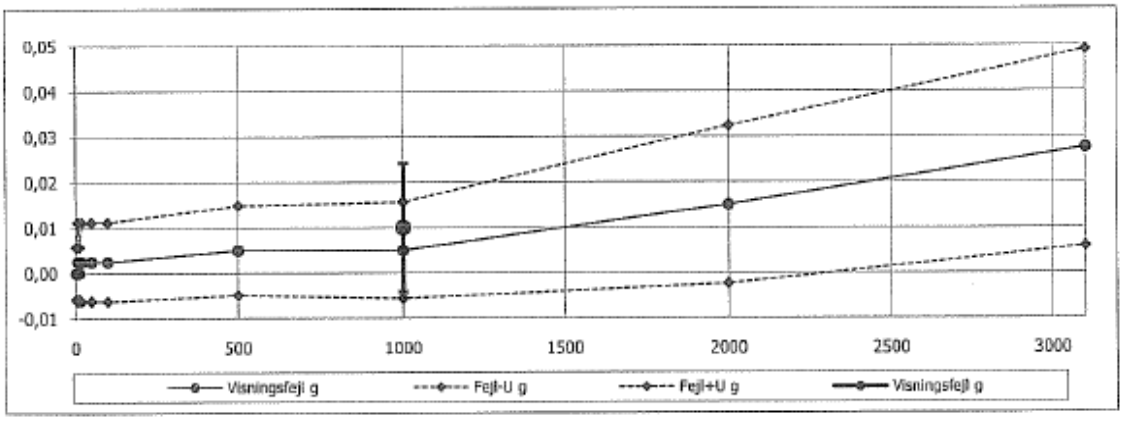
Lodderne blev kombineret til en opvejning.

### Målinger

| Belastning | 1. Visning | 2. Visning | 3. Visning | 4. Visning | 5. Visning | Belastningsform |
|---|---|---|---|---|---|---|
| g | g | g | g | g | g | |
| 2 | 2,00 | 2,00 | 2,00 | 2,00 | - | Central |
| 7 | 7,00 | 7,00 | 7,01 | 7,00 | - | Central |
| 12 | 12,00 | 12,00 | 12,00 | 12,00 | - | Central |
| 20 | 20,00 | 20,00 | 20,01 | 20,00 | - | Central |
| 50 | 50,00 | 50,00 | 50,01 | 50,00 | - | Central |
| 100 | 100,00 | 100,00 | 100,01 | 100,00 | - | Central |
| 500 | 500,00 | 500,00 | 500,01 | 500,01 | - | Central |
| 1000 | 1000,00 | 1000,00 | 1000,01 | 1000,01 | - | Central |
| 2000 | 2000,01 | 2000,01 | 2000,03 | 2000,01 | - | Central |
| 3100 | 3100,02 | 3100,02 | 3100,04 | 3100,03 | - | Central |
| 1000 | 1000,01 | 1000,00 | 1000,00 | 1000,02 | 1000,02 | Central/Excentrisk |

### Beregninger

| | | | | Kalibreringsresultater | | | |
|---|---|---|---|---|---|---|---|
| Belastning | Middelvisning | Spredning | Visningsfejl | Visningsfejl | Usikkerhed | k | Frihedsgrader |
| g | g | g | ‰ | g | g | | |
| 2 | 2,000 | 0,000 | 0,000 | 0,0000 | ± 0,0058 | 2,00 | >100 |
| 7 | 7,003 | 0,005 | 0,357 | 0,0025 | ± 0,0087 | 2,28 | 16,4 |
| 12 | 12,000 | 0,000 | 0,000 | 0,0000 | ± 0,0058 | 2,00 | >100 |
| 20 | 20,003 *) | 0,005 | 0,125 | 0,0025 | ± 0,0087 | 2,28 | 16,4 |
| 50 | 50,003 | 0,005 | 0,050 | 0,0025 | ± 0,0087 | 2,28 | 16,4 |
| 100 | 100,003 | 0,005 | 0,025 | 0,0025 | ± 0,0087 | 2,28 | 16,5 |
| 500 | 500,005 | 0,006 | 0,010 | 0,0050 | ± 0,0099 | 2,28 | 15,2 |
| 1000 | 1000,005 | 0,006 | 0,005 | 0,005 | ± 0,011 | 2,13 | 27,0 |
| 2000 | 2000,015 | 0,010 | 0,008 | 0,015 | ± 0,017 | 2,13 | 21,3 |
| 3100 | 3100,028 | 0,010 | 0,009 | 0,028 | ± 0,022 | 2,05 | 70,8 |
| 1000 | 1000,010 | Firkantfordelir | 0,010 | 0,010 | ± 0,014 | 2,00 | >100 |




*) Er OK med 2 decimaler

6/4-11 kl. L

## Oplysninger

**Certifikatnummer** 9.11-44-1038.
**Side** 3 af 3

**Sporbarhed** Resultaterne er sporbare til den internationale kilogram prototype i Paris Massenormalerne kalibreres af FORCE Technology. Dansk Institut for Fundamental Metrologi kalibrerer laboratoriets hovednormaler.

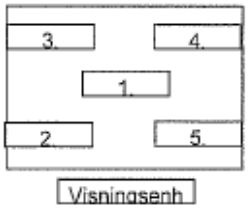
**Usikkerhed** Den ekspandere usikkerhed er angivet som standardusikkerheden multipliceret med dækningsfaktoren k, som for en t-fordeling med det beregnede antal effektive antal frihedsgrader svarer til en dækningssandsynlighed på ca. 95%. Standard-usikkerheden er fastlagt i overensstemmelse med EA-4/02.
Måleusikkerheden er sammensat af bidrag fra det kalibrerede udstyr og fra massenormalerne.
Bidraget fra det kalibrerede udstyr er sammensat af bidrag fra aflæsnings-nøjagtigheden og fra de aflæste visningers standardafvigelse.
Bidraget fra aflæsningsnøjagtigheden antages at være en firkantfordeling med fejlgrænser lig med halvdelen af udstyrets rapporterede delingsværdi.
Bidraget fra udstyrets standardafvigelse beregnes forskelligt afhængig af belastningsformen. Visninger aflæst med central belastning antages at være en normalfordeling. Visninger aflæst med central og excentrisk belastning antages at være en firkantfordeling hvis nedre grænse er den mindste aflæste visning og hvis øvre grænse er den største aflæste visning.
Bidraget fra massenormaler antages at være korrelleret med korrelations-faktoren 1. Bidraget fra en massenormal antages at være firkantfordelt med fejlgrænser lig med tolerancegrænserne for den OIML klasse som ses på forsiden. Massenormalerne kan være i overensstemmelse med en højere klasse.
De tre bidrag antages at være ukorrellerede.

**Miljø** Termometeret blev kalibreret af laboratoriet selv.
Barometeret blev kalibreret af laboratoriet selv.

Under kalibreringen er der foretaget én måling af miljøparametre.

**Belastningsform** Centrale belastninger blev placeret så tæt på vejeladdets centrum som muligt. Excentriske belastningsarealer og belastningsplacering blev fastlagt som foreskrevet i EN45501.

**Excentrisk placer** Ved excentrisk belastning blev lodderne placeret på en fjerdedel af vejeladdet. Teksterne på tegningen refererer til kolonnenavne i tabellerne benævnt målinger, belastningsform: Central/Excentrisk.



**Laboratoriekontrol af lodsæt nr. 70621 samt 500 g og 1000 g's lod (F2 lodder)**

Dato 26-04-2010
Initialer TIF Kontrol : LKJ/KU

| kontrol på vægt nr. 70504 | 1. vejning | 2. vejning | 3. vejning | 4. vejning | 5. vejning | gennemsnit | spredning | usikkerhedsgrænser | | usikkerhedsgrænser 2008 | | godkendelse |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 mg | 0,04999 | 0,04992 | 0,04996 | 0,04996 | 0,04996 | 0,04996 | 2,73861E-05 | 0,04994 | 0,04998 | 0,04988 | 0,05000 | ok |
| 1 g | 0,99998 | 1,00000 | 0,99999 | 1,00001 | 1,00000 | 1,00000 | 1,14016E-05 | 0,99999 | 1,00001 | 0,99992 | 1,00072 | ok |
| 2- g | 2,00009 | 2,00009 | 2,00008 | 2,00009 | 2,00008 | 2,00009 | 5,47723E-06 | 2,00008 | 2,00009 | 1,999983 | 2,000171 | ok |
| 2 g | 2,00000 | 2,00000 | 2,00002 | 1,99999 | 2,00000 | 2,00000 | 1,09545E-05 | 1,99999 | 2,00001 | 1,99989 | 2,000078 | ok |
| 5 g | 4,99990 | 4,99988 | 4,99987 | 4,99990 | 4,99989 | 4,99989 | 1,30384E-05 | 4,99988 | 4,99990 | 4,99979 | 5,00003 | ok |
| 10 g | 10,00002 | 10,00018 | 10,00017 | 10,00016 | 10,00015 | 10,00014 | 6,58027E-05 | 10,00009 | 10,00019 | 9,99999 | 10,00029 | ok |
| 20 g | 20,00018 | 20,00019 | 20,00016 | 20,00012 | 20,00013 | 20,00016 | 3,04956E-05 | 20,00013 | 20,00018 | 19,99999 | 20,00037 | ok |
| 20- g | 20,00018 | 20,00024 | 20,00020 | 20,00020 | 20,00019 | 20,00020 | 2,28035E-05 | 20,00018 | 20,00022 | 20,00006 | 20,00044 | ok |
| 50 g | 50,00006 | 50,00001 | 50,00002 | 50,00002 | 49,99998 | 50,00002 | 2,86356E-05 | 49,99999 | 50,00004 | 49,99978 | 50,00024 | ok |
| 100 g | 99,9998 | 99,9998 | 99,9998 | 99,9998 | 99,9998 | 99,9998 | 0 | 99,9998 | 99,9998 | 99,99942 | 100,00018 | ok |
| 200 g | 200,0009 | 200,0007 | 200,0006 | 200,0006 | 200,0005 | 200,0007 | 0,000151658 | 200,0005 | 200,0008 | 200,00017 | 200,00167 | ok |
| 200- g | 200,0001 | 200,0001 | 200,0001 | 200,0001 | 200,0002 | 200,0001 | 4,47214E-05 | 200,00008 | 200,00016 | 199,99982 | 200,00132 | ok |

| kontrol på vægt nr. 70671 | 1. vejning | 2. vejning | 3. vejning | 4. vejning | 5. vejning | gennemsnit | spredning | usikkerhedsgrænser | | usikkerhedsgrænser 2008 | | godkendelse |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 500 g | 499,99 | 500,01 | 500,00 | 500,00 | 500,00 | 500,00 | 0,007071068 | 499,9937 | 500,0063 | 499,9997 | 500,0035 | "ok" |
| 1 kg | 999,99 | 1000,00 | 1000,00 | 1000,01 | 1000,01 | 1000,00 | 0,0083666 | 999,9945 | 1000,0095 | 9999,9995 | 10000,0061 | "ok" |

Kriterierne for godkendelse af vejeresultaterne er følgende:

**Ligger gennemsnitsværdien med tilhørende usikkerhedsgrænser inden for de usikkerhedsgrænser der blev fastlagt ved kalibreringen d. 21/3-03 regnes værdien for uændret. Kan dette kriterium ikke opfyldes, skal det pågældende lod sendes til kalibrering, med mindre særlige forhold er gældende.**

Det ses af ovenstående kriterium ikke kan opfyldes for 500 g og 1 kg loddet. Årsagen hertil er højst sandsynligt at der er en større usikkerhed på de anvendte vægte end dem der anvendes ved kalibrering af lodsættet. Det vurderes derfor at den "sande værdi" for lodderne stadigvæk er OK, når de anvendes til funktionskontrol af maksimalbelastning på ovenstående tekniske vægte.

Grænseværdierne for 50 mg loddet er udvidet til 2 x usikkerheden for at imødegå at urimeligt skrapt krav

**Konklusion:**
Alle lodder godkendes 21/6-10 KIJ

# SLAGTERIERNES FORSKNINGSINSTITUT

## Kalibreringsrapport for SF n 71193

| | | | | | |
|---|---|---|---|---|---|
| Kalibr. Dato | **03-06-2010** | Type | | Din Nr / Type Nr | **indstiksføler** |
| Rum temp | **23,1** | Temp. område | | Anvendes med SF nr | **71192** |
| Kalibr. af | **elm** | Deling | **0,1** | | |

| Nominel temperatur | Ref. Visnin | Sand Temperatur | Brugs Visnin | Brugs Korrektion | Måle usikkerhed |
|---|---|---|---|---|---|
| **0** | **0,060** | **0,040** | **-0,100** | **0,140** | **0,109** |
| **5** | **5,160** | **5,140** | **4,900** | **0,240** | **0,108** |
| **10** | **10,060** | **10,040** | **9,900** | **0,140** | **0,109** |
| **20** | **20,010** | **19,990** | **19,800** | **0,190** | **0,108** |
| **40** | **40,270** | **40,270** | **40,200** | **0,070** | **0,108** |
| **60** | **60,090** | **60,087** | **60,000** | **0,087** | **0,108** |
| **80** | **79,950** | **79,943** | **79,900** | **0,043** | **0,108** |
| **100** | **100,340** | **100,330** | **100,400** | **-0,070** | **0,108** |

**Kalibreringen er foretaget i vandbad 70155 op imod referencetermometer bestående af føler 70162 og display 70161**

31. marts 2011 **Underskrevet d.** _____ Kontrolleret. af : **tif**

**Underskrift:** _____ **Underskrift :** _____

**Certificate, barometer**

The barometer reference can be downloaded at http://www.dmi.dk/dmi/tr02-17.pdf (last viewed 25-08-2011).

## 7.6. Calculation examples for reference measurements (for Phantom 1 only)

An example of measuring uncertainty assessment is presented here for Phantom 1 only, because the principle is the same for Phantom 2. It will give the reader an overview of the including uncertainty contributors.

### Determination of the volume of PMMA in Phantom 1

The volume of PMMA is measured with a pycnometer, a weight, measuring weights, a thermometer and a barometer. Table 18 shows the density and volumetric thermal expansion coefficient for PMMA.

***Table 18: Density and thermal expansion coefficient of PMMA.***

| Object | Material | Density [g/cm³] | Thermal expansion coefficient [$10^{-6}$ $K^{-1}$][2] |
|---|---|---|---|
| Meat and skin | PMMA | 1.19 | 70 |

The nominal value for PMMA is specified in Table 19 in mL.

***Table 19: Nominal values for PMMA in Phantom 1.***

| Material | Nominal value [mL] |
|---|---|
| PMMA | 3819.2 |

### Principle, method and conditions

**Measurement principle**
Measurement of volumes.

**Measurement method**
The measurements are performed with a pycnometer, a weight, a barometer, measuring weights and a thermometer. 6 measurements are carried out:

***Table 20: Measured values for PMMA in Phantom 1.***

| Measurement | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| PMMA [mL] | 3892.5106 | 3894.7570 | 3894.4762 | 3893.9146 | 3896.7226 | 3896.4418 |

**Measurement conditions**
Measurement temperature is 17.5 for PMMA.
Maximum temperature between equipment and phantom is 0.19 °C.
The variations are comprised within a range of ± 0.19 °C.

### List and discussion of the uncertainty contributors

Normally the uncertainty contribution from the barometer should be considered too, but since the accuracy is ± 0.15 hPa (1 hPa = 1 mbar), then it can be neglected. The reason is that the accuracy

[2] Note that the volumetric expansion coefficient can be calculated as $\beta \approx 3 \cdot \alpha$, where $\alpha$ is the informed linear expansion coefficient. This statement between a volumetric and a linear expansion coefficient is valid for isotropic materials (and for small expansions) and it is assumed that the used materials are isotropic.

of the barometer is too high to compare to the given values, which can be read off in the used NMKL procedure.

**$U_p$ – Uncertainty component coming from the measurement process**
This component is a type A evaluation and is estimated to follow a gaussian distribution. The volumes are measured 6 times in order to determine the contribution to the uncertainty due to repeatability. It is assumed that $u_p$ can be written as

$$u_p = STD \cdot h \text{ with n = 6 and h = 1.3 (safety factor)} \quad \textbf{(7.11)}$$

Hence *h* is a safety factor at 1.3, which is dependent on the number of measurements in relation to ISO 14253-2, which is *n = 6* in this case. *STD* is the standard deviation of the six measurements. Note that the *STD* is for PMMA. It gives $u_p = 1.583 mL \cdot 1.3$ = *2.0575 mL*.

**$U_w$ – Uncertainty component coming from the technical weight**
*This component is a type B evaluation and the reading error is estimated to follow a rectangular distribution (b = 0.6), so it gives* $u_w = error \cdot b = \frac{0.028\,g}{7.9\,g/mL} \cdot 0.6$ = *0.0021 mL*. *Hence the density for the measuring weights is used and is 7.9 g/mL for steel. Note that for the reading error, then the worst reading error is used.*

**$U_{t1}$ – Uncertainty component coming from environment temperature difference for instrument**
The measurement temperature is observed to be 17.5 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 2.5 based on the difference between the observed temperature and the standard reference temperature.
The "instrument" is assumed to be distilling water, since it is used to determine the volume of the polymer parts of the phantom. The linear coefficients of thermal expansion for distil water is
$\alpha_{water}$ = 69 x $10^{-6}$ $K^{-1}$.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as
$\beta_{water} \approx 3 \cdot \alpha_{water}$.

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t1} = \Delta T \cdot \beta_{water} \cdot V_{\max} \cdot b = 2.5°C \cdot \left(69 \cdot 10^{-6}\, K^{-1}\right) \cdot 3 \cdot 3896.8\, mL \cdot 0.7$ = *1.4116 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 3896.8 mL (a corrected value for PMMA).

**$U_{t2}$ – Uncertainty component coming from environment temperature difference for artefact**
The measurement temperature is observed to be 17.5 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 2.5 based on the difference between the observed temperature and the standard reference temperature.
In this case the linear coefficients of thermal expansion has been considered (PMMA) and is
$\alpha_{artefact}$ = 70 x $10^{-6}$ $K^{-1}$.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as $\beta_{artefact} \approx 3 \cdot \alpha_{artefact}$ .

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t2} = \Delta T \cdot \beta_{artefact} \cdot V_{\max} \cdot b = 2.5°C \cdot \left(70 \cdot 10^{-6}\ K^{-1}\right) \cdot 3 \cdot 3896.8\,mL \cdot 0.7$ = *1.4321 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 3896.8 mL (a corrected value for PMMA).

**$U_{t3}$ – Uncertainty component coming from the deviation from standard reference temperature**
The estimated range of deviation from standard temperature is ± 0.19.
The difference between the two linear coefficients of thermal expansion is
$\Delta\alpha = \left|\alpha_{artefact} - \alpha_{water}\right| = \left|70 - 69\right| \times 10^{-6}\ K^{-1}$ = *1 x10$^{-6}$ K$^{-1}$*.

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t3} = \Delta T \cdot \Delta\beta \cdot V_{\max} \cdot b = 0.19°C \cdot \left(1 \cdot 10^{-6}\ K^{-1}\right) \cdot 3 \cdot 3896.8\,mL \cdot 0.7$ = *0.0016 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 3896.8 mL (a corrected value for PMMA).

**$U_r$ – Uncertainty component coming from measuring weights**
A measuring weight of nominal weight of 1 kg is used as reference. Note that the uncertainty is bigger for this measuring weight compared to the lightweight measuring weights. The weight coincides within ± 0.0095 g. It is assumed that the measuring weight is made of steel. Thus, a rectangular distribution is assumed (*b = 0.6*). Then the component can be found as
$u_r = \frac{0.0095\,g}{7.9\,g/mL} \times 0.6$ = *0.0007 mL*.

**$U_a$ – Uncertainty component coming from water absorption for artefact**
Water absorption at 23 °C is 0.17 % according to the manufacturer, where EN ISO 62 was used.
A rectangular distribution is assumed (*b = 0.6*), so the limit value is
$u_a = \lambda_{artefact} \cdot V_{\max} \cdot b = \frac{0.17}{100} \cdot 3896.8\,mL \cdot 0.6$ = *3.9747 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 3896.8 mL (a corrected value for PMMA).

## Compensation of systematic errors

### Compensation of systematic error due to the temperature

The compensation of systematic error due to the temperature should be made manually. The corrected volume with reference to the standard reference temperature is given in the table below and is calculated using (7.3).

***Table 21: Compensation of average of measured values for PMMA in Phantom 1.***

| Material | Volume [mL] | Corrected volume [mL] |
|---|---|---|
| PMMA | 3894.8 | 3896.8 |

## Determination of the volume of PE in Phantom 1

The volume of PE is measured with a pycnometer, a weight, measuring weights, a thermometer and a barometer. Table 22 shows the density and volumetric thermal expansion coefficient for PE.

***Table 22: Density and thermal expansion coefficient of PE.***

| Object | Material | Density [g/cm³] | Thermal expansion coefficient [$10^{-6}$ $K^{-1}$][3] |
|---|---|---|---|
| Fat | PE | 0.95 | 200 |

The nominal value for PE is specified in Table 23 in mL.

***Table 23: Nominal value for PE in Phantom 1.***

| Material | Nominal value [mL] |
|---|---|
| PE | 1342.5 |

## Principle, method and conditions

### Measurement principle
Measurement of volumes.

### Measurement method
The measurements are performed with a pycnometer, a weight, a barometer, measuring weights and a thermometer. 6 measurements are carried out:

***Table 24: Measured values for PE in Phantom 1.***

| Measurement | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| PE [mL] | 1273.2607 | 1273.1801 | 1272.6155 | 1273.0188 | 1273.0994 | 1273.4220 |

### Measurement conditions
Measurement temperature is 16.4 for PE.
Maximum temperature between equipment and phantom is 0.19 °C.
The variations are comprised within a range of ± 0.19 °C.

## List and discussion of the uncertainty contributors

Normally the uncertainty contribution from the barometer should be considered too, but since the accuracy is ± 0.15 hPa (1 hPa = 1 mbar), then it can be neglected. The reason is that the accuracy of the barometer is too high to compare to the given values, which can be read off in the used NMKL procedure.

### $U_p$ – Uncertainty component coming from the measurement process
This component is a type A evaluation and is estimated to follow a gaussian distribution. The volumes are measured 6 times in order to determine the contribution to the uncertainty due to repeatability. It is assumed that $u_p$ can be written as

[3] Note that the volumetric expansion coefficient can be calculated as $\beta \approx 3 \cdot \alpha$, where $\alpha$ is the informed linear expansion coefficient. This statement between a volumetric and a linear expansion coefficient is valid for isotropic materials (and for small expansions) and it is assumed that the used materials are isotropic.

$u_p = STD \cdot h$ with n = 6 and h = 1.3 (safety factor) ***(7.12)***

Hence *h* is a safety factor at 1.3, which is dependent on the number of measurements in relation to ISO 14253-2, which is *n = 6* in this case. *STD* is the standard deviation of the six measurements. Note that the *STD* is for PE. It gives $u_p = 0.275\,mL \cdot 1.3$ = *0.3571 mL*.

**$U_w$ – Uncertainty component coming from the technical weight**

*This component is a type B evaluation and the reading error is estimated to follow a rectangular distribution (b = 0.6), so it gives* $u_w = error \cdot b = \frac{0.028\,g}{7.9\,g/mL} \cdot 0.6$ = *0.0021 mL. Hence the density for the measuring weights is used and is 7.9 g/mL for steel. Note that for the reading error, then the worst reading error is used.*

**$U_{t1}$ – Uncertainty component coming from environment temperature difference for instrument**

The measurement temperature is observed to be 16.4 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 3.6 based on the difference between the observed temperature and the standard reference temperature.
The "instrument" is assumed to be distilling water, since it is used to determine the volume of the polymer parts of the phantom. The linear coefficients of thermal expansion for distil water is $\alpha_{water}$ = *69 x 10$^{-6}$ K$^{-1}$*.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as $\beta_{water} \approx 3 \cdot \alpha_{water}$.

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t1} = \Delta T \cdot \beta_{water} \cdot V_{\max} \cdot b = 3.6\,°C \cdot \left(69 \cdot 10^{-6}\,K^{-1}\right) \cdot 3 \cdot 1275.8\,mL \cdot 0.7$ = *0.6655 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 1275.8 mL (a corrected value for PE).

**$U_{t2}$ – Uncertainty component coming from environment temperature difference for artefact**

The measurement temperature is observed to be 16.4 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 3.6 based on the difference between the observed temperature and the standard reference temperature.
In this case the linear coefficients of thermal expansion has been considered (PE) and is $\alpha_{artefact}$ = *200 x 10$^{-6}$ K$^{-1}$*.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as $\beta_{artefact} \approx 3 \cdot \alpha_{artefact}$ .

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t2} = \Delta T \cdot \beta_{artefact} \cdot V_{\max} \cdot b = 3.6\,°C \cdot \left(200 \cdot 10^{-6}\,K^{-1}\right) \cdot 3 \cdot 1275.8\,mL \cdot 0.7$ = *1.9291 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 1275.8 mL (a corrected value for PE).

**$U_{t3}$ – Uncertainty component coming from the deviation from standard reference temperature**

The estimated range of deviation from standard temperature is ± 0.19.
The difference between the two linear coefficients of thermal expansion is

$\Delta\alpha = \left|\alpha_{artefact} - \alpha_{water}\right| = \left|200 - 69\right| \times 10^{-6}\, K^{-1}$ = *131 x10$^{-6}$ K$^{-1}$*.

A U- distribution is assumed (*b = 0.7*), so the limit value is

$u_{t3} = \Delta T \cdot \Delta\beta \cdot V_{\max} \cdot b = 0.19\,°C \cdot \left(131 \cdot 10^{-6}\, K^{-1}\right) \cdot 3 \cdot 1275.8\ mL \cdot 0.7$ = *0.0667 mL*.

Note that the used volume ($V_{max}$) is the measured volume and is 1275.8 mL (a corrected value for PE).

**$U_r$ – Uncertainty component coming from measuring weights**

A measuring weight of nominal weight of 1 kg is used as reference. Note that the uncertainty is bigger for this measuring weight compared to the lightweight measuring weights. The weight coincides within ± 0.0095 g. It is assumed that the measuring weight is made of steel. Thus, a rectangular distribution is assumed (*b = 0.6*). Then the component can be found as

$u_r = \frac{0.0095\,g}{7.9\,g/mL} \times 0.6$ = *0.0007 mL*.

**$U_a$ – Uncertainty component coming from water absorption for artefact**

Water absorption at 23 °C is 0.01 % according to the manufacturer, where EN ISO 62 was used.
A rectangular distribution is assumed (*b = 0.6*), so the limit value is

$u_a = \lambda_{artefact} \cdot V_{\max} \cdot b = \frac{0.01}{100} \cdot 1275.8\,mL \cdot 0.6$ = *0.0766 mL*.

Note that the used volume ($V_{max}$) is the measured volume and is 1275.8 mL (a corrected value for PE).

## Compensation of systematic errors

### Compensation of systematic error due to the temperature

The compensation of systematic error due to the temperature should be made manually. The corrected volume with reference to the standard reference temperature is given in the table below and is calculated using (7.3).

***Table 25: Compensation of average of measured values for PE in Phantom 1.***

| Material | Volume [mL] | Corrected volume [mL] |
|---|---|---|
| PE | 1273.1 | 1275.8 |

## Determination of the volume of PVC in Phantom 1

The volume of PVC is measured with a pycnometer, a weight, measuring weights, a thermometer and a barometer. Table 26 shows the density and volumetric thermal expansion coefficient for PVC.

***Table 26: Density and thermal expansion coefficient of PVC.***

| Object | Material | Density [g/cm³] | Thermal expansion coefficient [$10^{-6}$ $K^{-1}$][4] |
|---|---|---|---|
| Marrow and bone | PVC | 1.38 | 75 |

The nominal value for PVC is specified in Table 27 in mL.

***Table 27: Nominal values for PVC in Phantom 1.***

| Material | Nominal value [mL] |
|---|---|
| PVC | 8.3 |

## Principle, method and conditions

### Measurement principle
Measurement of volumes.

### Measurement method
The measurements are performed with a pycnometer, a weight, a barometer, measuring weights and a thermometer. 6 measurements are carried out:

***Table 28: Measured values for PVC in Phantom 1.***

| Measurement | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| PVC [mL] | 7.7586 | 7.8660 | 7.7857 | 7.7857 | 7.8861 | 7.8760 |

### Measurement conditions
Measurement temperature is 17.5 for PVC.
Maximum temperature between equipment and phantom is 0.19 °C.
The variations are comprised within a range of ± 0.19 °C.

## List and discussion of the uncertainty contributors

Normally the uncertainty contribution from the barometer should be considered too, but since the accuracy is ± 0.15 hPa (1 hPa = 1 mbar), then it can be neglected. The reason is that the accuracy of the barometer is too high to compare to the given values, which can be read off in the used NMKL procedure.

### $U_p$ – Uncertainty component coming from the measurement process
This component is a type A evaluation and is estimated to follow a gaussian distribution. The volumes are measured 6 times in order to determine the contribution to the uncertainty due to repeatability. It is assumed that $u_p$ can be written as

[4] Note that the volumetric expansion coefficient can be calculated as $\beta \approx 3 \cdot \alpha$, where $\alpha$ is the informed linear expansion coefficient. This statement between a volumetric and a linear expansion coefficient is valid for isotropic materials (and for small expansions) and it is assumed that the used materials are isotropic.

$u_p = STD \cdot h$ with n = 6 and h = 1.3 (safety factor) ***(7.13)***

Hence *h* is a safety factor at 1.3, which is dependent on the number of measurements in relation to ISO 14253-2, which is *n = 6* in this case. *STD* is the standard deviation of the six measurements. Note that the *STD* is for PVC. It gives $u_p = 0.0557\,mL \cdot 1.3$ = *0.0724 mL*.

**$U_w$ – Uncertainty component coming from the technical weight**

*This component is a type B evaluation and the reading error is estimated to follow a rectangular distribution (b = 0.6), so it gives* $u_w = error \cdot b = \frac{0.028\,g}{7.9\,g/mL} \cdot 0.6$ = *0.0021 mL*. *Hence the density for the measuring weights is used and is 7.9 g/mL for steel. Note that for the reading error, then the worst reading error is used.*

**$U_{t1}$ – Uncertainty component coming from environment temperature difference for instrument**

The measurement temperature is observed to be 17.5 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 2.5 based on the difference between the observed temperature and the standard reference temperature.
The "instrument" is assumed to be distilling water, since it is used to determine the volume of the polymer parts of the phantom. The linear coefficients of thermal expansion for distil water is $\alpha_{water}$ = 69 x $10^{-6}$ $K^{-1}$.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as $\beta_{water} \approx 3 \cdot \alpha_{water}$.

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t1} = \Delta T \cdot \beta_{water} \cdot V_{\max} \cdot b = 2.5°C \cdot \left(69 \cdot 10^{-6}\,K^{-1}\right) \cdot 3 \cdot 7.8\,mL \cdot 0.7$ = *0.0028 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 7.8 mL (a corrected value for PVC).

**$U_{t2}$ – Uncertainty component coming from environment temperature difference for artefact**

The measurement temperature is observed to be 17.5 °C (biggest difference from standard reference temperature at 20 °C). Therefore a temperature difference is assumed to be ± 2.5 based on the difference between the observed temperature and the standard reference temperature.
In this case the linear coefficients of thermal expansion has been considered (PVC) and is $\alpha_{artefact}$ = 75 x $10^{-6}$ $K^{-1}$.

It is assumed that it is isotropic, so the volumetric thermal expansion coefficient can be found as $\beta_{artefact} \approx 3 \cdot \alpha_{artefact}$ .

A U- distribution is assumed (*b = 0.7*), so the limit value is
$u_{t2} = \Delta T \cdot \beta_{artefact} \cdot V_{\max} \cdot b = 2.5°C \cdot \left(75 \cdot 10^{-6}\,K^{-1}\right) \cdot 3 \cdot 7.8\,mL \cdot 0.7$ = *0.0031 mL*.
Note that the used volume ($V_{max}$) is the measured volume and is 7.8 mL (a corrected value for PVC).

**$U_{t3}$ – Uncertainty component coming from the deviation from standard reference temperature**

The estimated range of deviation from standard temperature is ± 0.19.
The difference between the two linear coefficients of thermal expansion is

$$\Delta\alpha = \left|\alpha_{artefact} - \alpha_{water}\right| = \left|75 - 69\right| \times 10^{-6}\, K^{-1} = 6 \times 10^{-6}\, K^{-1}.$$

A U- distribution is assumed ($b = 0.7$), so the limit value is

$$u_{t3} = \Delta T \cdot \Delta\beta \cdot V_{\max} \cdot b = 0.19\,°C \cdot \left(6 \cdot 10^{-6}\, K^{-1}\right) \cdot 3 \cdot 7.8\,mL \cdot 0.7 = \underline{0.0000\ mL}.$$

Note that the used volume ($V_{max}$) is the measured volume and is 7.8 mL (a corrected value for PVC).

**$U_r$ – Uncertainty component coming from measuring weights**

A measuring weight of nominal weight of 1 kg is used as reference. Note that the uncertainty is bigger for this measuring weight compared to the lightweight measuring weights. The weight coincides within ± 0.0095 g. It is assumed that the measuring weight is made of steel. Thus, a rectangular distribution is assumed ($b = 0.6$). Then the component can be found as

$$u_r = \frac{0.0095\,g}{7.9\,g/mL} \times 0.6 = \underline{0.0007\ mL}.$$

**$U_a$ – Uncertainty component coming from water absorption for artefact**

Water absorption at 23 °C is 0.1 % according to the manufacturer, where EN ISO 62 was used.
A rectangular distribution is assumed ($b = 0.6$), so the limit value is

$$u_a = \lambda_{artefact} \cdot V_{\max} \cdot b = \frac{0.1}{100} \cdot 7.8\,mL \cdot 0.6 = \underline{0.0047\ mL}.$$

Note that the used volume ($V_{max}$) is the measured volume and is 7.8 mL (a corrected value for PVC).

## Compensation of systematic errors

### Compensation of systematic error due to the temperature

The compensation of systematic error due to the temperature should be made manually. The corrected volume with reference to the standard reference temperature is given in the table below and is calculated using (7.3).

***Table 29: Compensation of average of measured values for PVC in Phantom 1.***

| Material | Volume [mL] | Corrected volume [mL] |
|---|---|---|
| PVC | 7.8 | 7.8 |

## 7.7. Summary of uncertainty budgets

Note that all units are applied in mL.

### Phantom 1:

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 1.5827 mL | 1.5827 | 1.3 | 2.0575 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 2.5 °C | 2.0166 | 0.7 | 1.4116 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 2.5 °C | 2.0459 | 0.7 | 1.4321 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0.0023 | 0.7 | 0.0016 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.17 % | 6.6245 | 0.6 | 3.9747 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 4.9067 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | **9.8134** |

| **Measuring result** | **PMMA** | **Y ± U(Y) =** | **3896.8 ± 9.8 mL** |
|---|---|---|---|

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 0.2747 mL | 0.2747 | 1.3 | 0.3571 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 3.6 °C | 0.9509 | 0.7 | 0.6655 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 3.6 °C | 2.7560 | 0.7 | 1.9291 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0.0953 | 0.7 | 0.0667 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.01 % | 0.1277 | 0.6 | 0.0766 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 2.0742 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | **4.1483** |

| **Measuring result** | **PE** | **Y ± U(Y) =** | **1275.9 ± 4.1 mL** |
|---|---|---|---|

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 0.0557 mL | 0.0557 | 1.3 | 0.0724 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 2.5 °C | 0,0040 | 0.7 | 0.0028 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 2.5 °C | 0,0044 | 0.7 | 0.0031 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0,0000 | 0.7 | 0.0000 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.1 % | 0.0078 | 0.6 | 0.0047 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 0.0727 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | 0.1454 |

| **Measuring result** | **PVC** | **Y ± U(Y) =** | **7.8 ± 0.1 mL** |
|---|---|---|---|

## Phantom 2:

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 0.2860 mL | 0.2860 | 1.3 | 0.3718 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 0.3 °C | 0.1897 | 0.7 | 0.1328 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 0.3 °C | 0.1924 | 0.7 | 0.1347 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0.0017 | 0.7 | 0.0012 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.17 % | 5.1940 | 0.6 | 3.1164 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 3.1442 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | **6.2883** |

**Measuring result** **PMMA** **Y ± U(Y) =** **3055.3 ± 6.3 mL**

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 0.2077 mL | 0.2077 | 1.3 | 0.2700 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 0.3 °C | 0.1316 | 0.7 | 0.0921 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 0.3 °C | 0.3813 | 0.7 | 0.2669 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0,1581 | 0.7 | 0.1107 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.01 % | 0.2118 | 0.6 | 0.1271 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 0.4255 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | **0.8510** |

**Measuring result** **PE** **Y ± U(Y) =** **2118.3 ± 0.9 mL**

| Component name | | Evaluation type | Distribution type | Number of measurements | Variation limit [influence units] | Variation limit [mL] | Distribution factor | Uncert. Comp. [mL] |
|---|---|---|---|---|---|---|---|---|
| $u_P$ | Procedure | A | Gaussian | 6 | 0.0052 mL | 0.0052 | 1.3 | 0.0067 |
| $u_w$ | Technical weight | B | Rect. | - | 0.0035 mL | 0.0035 | 0.6 | 0.0021 |
| $u_{t1}$ | Temperature | B | U-shaped | - | 0.2 °C | 0.0000 | 0.7 | 0.0002 |
| $u_{t2}$ | Temperature | B | U-shaped | - | 0.2 °C | 0.0000 | 0.7 | 0.0002 |
| $u_{t3}$ | Temperature | B | U-shaped | - | 0.19 °C | 0.0000 | 0.7 | 0.0000 |
| $u_r$ | Component coming from measuring weights | B | Rect. | - | 0.0012 mL | 0.0012 | 0.6 | 0.0007 |
| $u_a$ | Water absorption | B | Rect. | - | 0.1 % | 0.0077 | 0.6 | 0.0046 |
| **Combined standard uncertainty** | | | | $u_c$ | | | | 0.0085 |
| **Expanded uncertainty (k = 2)** | | | | **U** | | | | **0.0170** |

**Measuring result** **PVC** **Y ± U(Y) =** **7.7 ± 0.0 mL**

## 7.8. Data for ANOVA tests

| **Phantom 1** | Time (B) | | | | | | |
|---|---|---|---|---|---|---|---|
| Material (A) | November 2011 | | December 2011 | | February 2012 | | yi... |
| PMMA | 3672 | 35539 | 3958 | 36520 | 3803 | 35904 | 107963 |
| | 4077 | | 4115 | | 4088 | | |
| | 4153 | | 4177 | | 4162 | | |
| | 3643 | | 3911 | | 3708 | | |
| | 4058 | | 4112 | | 4071 | | |
| | 4144 | | 4175 | | 4152 | | |
| | 3582 | | 3823 | | 3744 | | |
| | 4063 | | 4088 | | 4038 | | |
| | 4148 | | 4161 | | 4137 | | |
| PE | 1912 | 14739 | 1706 | 14084 | 1766 | 13984 | 42807 |
| | 1460 | | 1499 | | 1446 | | |
| | 1431 | | 1486 | | 1407 | | |
| | 1969 | | 1723 | | 1848 | | |
| | 1498 | | 1479 | | 1455 | | |
| | 1468 | | 1458 | | 1404 | | |
| | 2033 | | 1793 | | 1795 | | |
| | 1501 | | 1485 | | 1462 | | |
| | 1468 | | 1454 | | 1401 | | |
| PVC | 32 | 294 | 30 | 285 | 34 | 350 | 929 |
| | 29 | | 26 | | 33 | | |
| | 32 | | 30 | | 34 | | |
| | 37 | | 30 | | 35 | | |
| | 36 | | 27 | | 36 | | |
| | 37 | | 30 | | 35 | | |
| | 31 | | 37 | | 45 | | |
| | 29 | | 38 | | 54 | | |
| | 31 | | 37 | | 45 | | |
| y.j.. | | 50573 | | 50888 | | 50238 | 151699 |

yij..

| | B | | |
|---|---|---|---|
| A | November 2011 | December 2011 | February 2012 |
| PMMA | 35539 | 36520 | 35904 |
| PE | 14739 | 14084 | 13984 |
| PVC | 294 | 285 | 350 |

| n (replicates) | = | 9 |
|---|---|---|

| **Phantom 2** | | | Time (B) | | | | |
|---|---|---|---|---|---|---|---|
| Material (A) | November 2011 | | December 2011 | | February 2012 | | yi… |
| PMMA | 2894 | 27164 | 2813 | 26840 | 2800 | 26545 | 80550 |
| | 3068 | | 3052 | | 3032 | | |
| | 3117 | | 3102 | | 3087 | | |
| | 2922 | | 2819 | | 2760 | | |
| | 3065 | | 3041 | | 3025 | | |
| | 3112 | | 3091 | | 3084 | | |
| | 2831 | | 2770 | | 2694 | | |
| | 3052 | | 3051 | | 2998 | | |
| | 3104 | | 3102 | | 3064 | | |
| PE | 2745 | 23314 | 2846 | 23758 | 2787 | 23576 | 70648 |
| | 2506 | | 2570 | | 2524 | | |
| | 2521 | | 2557 | | 2501 | | |
| | 2711 | | 2803 | | 2823 | | |
| | 2511 | | 2552 | | 2520 | | |
| | 2521 | | 2531 | | 2499 | | |
| | 2786 | | 2848 | | 2880 | | |
| | 2502 | | 2535 | | 2532 | | |
| | 2512 | | 2516 | | 2510 | | |
| PVC | 27 | 245 | 30 | 258 | 27 | 258 | 761 |
| | 24 | | 26 | | 24 | | |
| | 27 | | 30 | | 27 | | |
| | 27 | | 32 | | 26 | | |
| | 24 | | 27 | | 24 | | |
| | 27 | | 32 | | 26 | | |
| | 30 | | 28 | | 35 | | |
| | 27 | | 25 | | 34 | | |
| | 30 | | 28 | | 35 | | |
| y.j.. | | 50724 | | 50856 | | 50379 | 151959 |

yij..

| | B | | |
|---|---|---|---|
| A | November 2011 | December 2011 | February 2012 |
| PMMA | 27164 | 26840 | 26545 |
| PE | 23314 | 23758 | 23576 |
| PVC | 245 | 258 | 258 |

| | | |
|---|---|---|
| n (replicates) | = | 9 |