MIKES METROLOGIA

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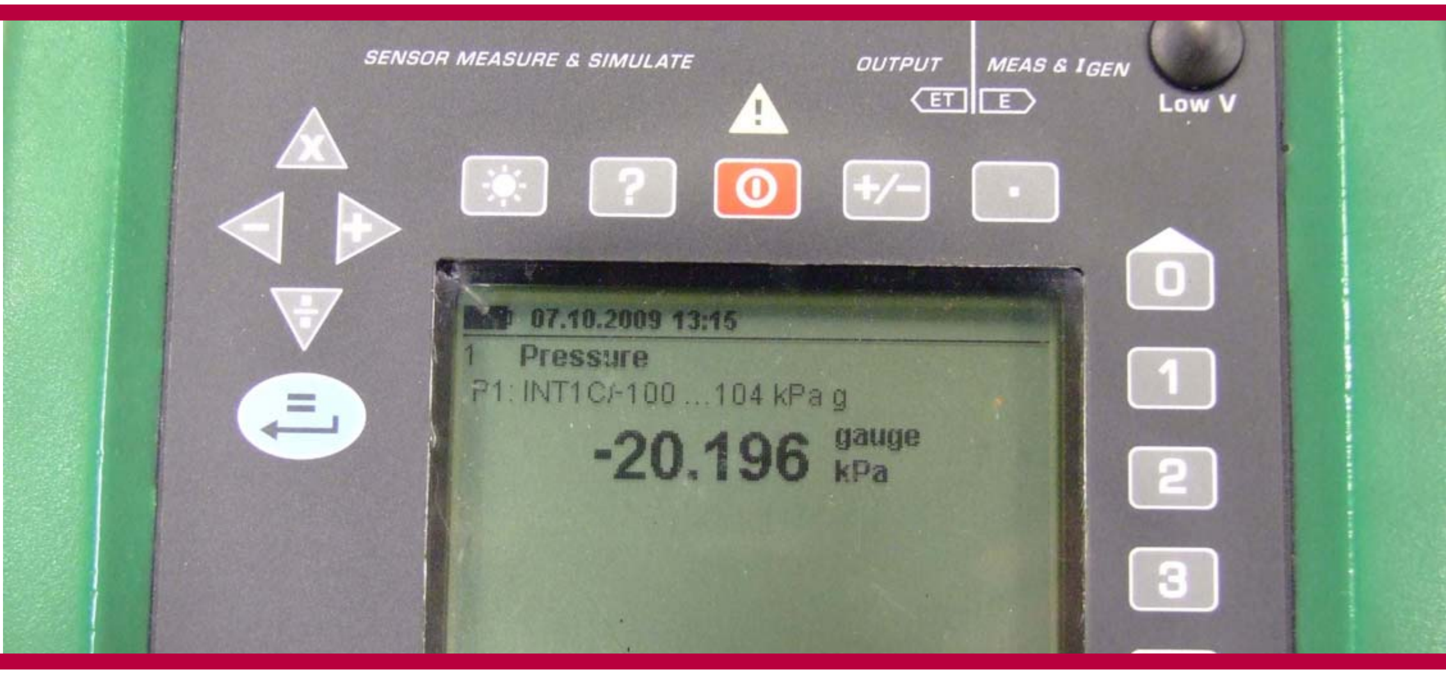

Negative gauge pressure comparison

Range -95 kPa to + 95 kPa

EURAMET Project 1131

Markku Rantanen, Sari Saxholm, Aykurt Altintas, Richard Pavis and Guliko Peterson

Centre for Metrology and Accreditation

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Abstract

A pressure comparison in the negative gauge pressure range was arranged in 2009. The participating laboratories were CMI / Czech Republic, FORCE Technology / Denmark, AS Metrosert / Estonia and MIKES / Finland. Negative gauge pressures are a common range for pressure calibrations although uncertainty requirements are generally not very high.

The results from the four participating laboratories suggest that calibrations in the negative gauge pressure range are not as easy as expected. Some of the claimed uncertainties were perhaps too optimistic, and the large variation in the results made it difficult to generate consistent reference values. The agreement of the results at positive gauge pressures on the same transfer standard was much better. Obviously there is a need for further comparisons in the negative gauge pressure range.

The transfer standard was a multifunction calibrator Beamex MC5 equipped with an internal pressure module for the range -100 kPa to 104 kPa in the gauge mode. The resolution of the display was 0,001 kPa. The stability of the transfer standard was good.

The comparison was registered as EURAMET Project No. 1131 and as the supplementary comparison EURAMET.M.P.-S8 in the BIPM key comparison database.

Contents

1 Introduction

A pressure comparison in the negative gauge pressure range between CMI / Czech Republic, MIKES / Finland, FORCE Technology / Denmark and Metrosert / Estonia was arranged in 2009. The comparison was registered as EURAMET project No. 1131 and as the supplementary comparison EURAMET.M.P.-S8 in the BIPM key comparison database.

Negative gauge pressures are a common range for pressure calibrations although uncertainty requirements are generally not very high. Not many laboratories have included their calibration and measurement capabilities for negative gauge pressures in the CMC tables of BIPM, and no key comparisons are specified in this range on the CCM or regional level. The Finnish national comparison [1] in 2005 is one of the few reported comparisons in the negative gauge pressure range.

Figure 1 illustrates the CMC uncertainties of some EURAMET countries at the nominal pressure -80 kPa. For instance France, Italy, Sweden and the Netherlands have no lines for negative gauge pressures in the CMC tables at present (August 2009).

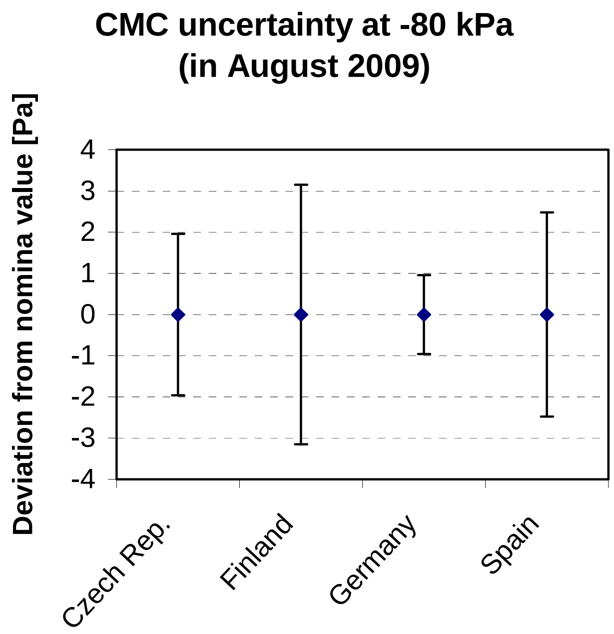

Figure 1. The CMC uncertainties corresponding to -80 kPa gauge pressure at CMI/Czech Republic, MIKES/Finland, PTB/Germany and CEM/Spain (some examples of EURAMET countries)

2 Participants and their standards

MIKES

The reference standard of MIKES used in this comparison was a DH Instruments PG7607 pressure balance s/n 397 equipped with a piston/cylinder assembly s/n 451. The effective area of the piston/cylinder unit, nominally 1960 mm^2, was determined with dimensional measurements at LNE in September – October 2007 (certificate H090649/1) and with pressure measurements at MIKES in July 2008 (certificate M-08P078). The pressure measurements of MIKES are traceable to LNE.

The 35 kg weight set DHI s/n 2229 used on the pressure balance was calibrated at MIKES in May 2009 (certificate M-09M014).

The negative gauge pressures were generated in the bell jar of the pressure balance.

Metrosert

The reference standard of Metrosert was a Pressurements 6100-5L pressure balance s/n 59125. The effective area of the piston/cylinder assembly s/n X0131 is traceable to MIKES (the latest certificate M-08P106, dated 9.10.2008). The weight set was calibrated at the mass laboratory of Metrosert in August 2008 (certificate ATLM-08/0494).

The negative gauge pressures were generated in the bell jar of the pressure balance.

FORCE Technology

FORCE Technology used two different pressure balances for their measurements. The first one was a Budenberg type 239 pressure balance s/n 18130 with piston/cylinder assembly s/n H369, which can be used for negative pressures by inverting the piston/cylinder assembly. No bell jar is needed for negative gauge pressures. The effective area, nominally 161 mm^2, and the weight set are traceable to PTB, Germany. The latest calibration was carried out in September 2007 (certificate 0077 PTB 07). The results of FORCE Technology for negative gauge pressures were obtained using this instrument.

For the positive side the standard was a Budenberg type 240L pressure balance s/n 18071 with piston/cylinder s/n H 425. The effective area, nominally 161 mm^2, and the weight set are traceable to PTB, Germany. The latest calibration was carried out in March 2006 (certificate 0022 PTB 06).

CMI

The reference standard of CMI used in this comparison was a DH Instruments PG7601 pressure balance s/n 127 equipped with a piston/cylinder assembly s/n 368. The effective area of the piston/cylinder unit, nominally 980 mm^2, is traceable (the latest certificate 6013-KL-P061-08 from December 2008) to a piston/cylinder assembly s/n 248 of the same nominal effective area which was evaluated from dimensional measurements.

The 35 kg weight set DHI s/n 2089 used on the pressure balance was calibrated at CMI in October 2008 (certificate 6012-KL-H052-08). The negative gauge pressures were generated in the bell jar of the pressure balance.

A detailed description of the CMI instrumentation for negative gauge pressures is found in Ref. [2].

3 Transfer standard

The transfer standard used was a multifunction calibrator Beamex MC5 s/n 25516865 equipped with an internal pressure module INT1C. The transfer standard was made available by Beamex Oy Ab, Pietarsaari, Finland.

The nominal pressure range of the pressure module INT1C is from -100 kPa to + 104 kPa in the gauge mode. The resolution was 0,001 kPa.

4 Measurement instructions

The measurement instructions were given in the measurement protocol dated 22.4.2009 (Appendix 1).

The nominal pressures to be measured were 0 kPa, -20 kPa, -40 hPa, -60 kPa, -80 kPa and -95 kPa

The transmitting gas was specified as dry air or nitrogen.

A minimum stabilisation time of 3 hours was specified with the mains power switched on and the pressure connection opened to the atmosphere. The following pre-pressurisation and measurement schedule was specified:

1. Pre-pressurisation 2 or 3 times to -95kPa
2. 3 – 5 minutes at atmospheric pressure
3. Zeroing
4. Measurements at the specified nominal pressures 0 kPa to -95 kPa
5. Approximately 2 minutes at -98 kPa ± 2 kPa
6. Measurements at specified nominal pressures from -95 kPa to 0 kPa
7. 3 – 5 minutes at atmospheric pressure
8. Zeroing
9. Repetition of steps from 2 to 8 at least two times to obtain at least 3 results at each point.

The results in increasing and decreasing directions were treated separately to minimise hysteresis effects. For the same reason it was stated that the pressure on the transfer standard should not be set to zero between successive nominal pressures.

One of the objectives in the project was to compare measurement capabilities in the negative and positive gauge pressures at the same nominal values.

The results were to be presented as average deviations and measurement uncertainties with coverage factor k = 2 at each nominal pressure.

5 Measurements and the presentation of results

The measurements were carried out four times at MIKES and once at Metrosert, FORCE Technology and CMI according to the following schedule:

MIKES (M1)	31.03.2009
MIKES (M2)	20.04.2009
Metrosert	29.04.-01.05.2009
FORCE Technology	07.-11.05.2009
CMI	25.05.2009
MIKES (M3)	05. – 08.06.2009
MIKES (M4)	12.6.2009

Each laboratory presented its results as calibration certificates, and sent the certificates or summaries of the results to Dr. Wladimir Sabuga, PTB, Germany. Dr. Sabuga sent the results to MIKES 30.7.2009 after receiving all of them.

The result set from the second measurement at MIKES (M2) was used for the comparison, as stated in advance in the measurement instructions. The other MIKES results were used to control the stability of the transfer standard.

In August, Metrosert delivered corrections for some misprints and Force Technology delivered a new certificate with corrected uncertainty values. The influence of the corrections was very small.

6 Stability of the transfer standard

The stability of the transfer standard was determined from the results of the four measurements at MIKES.

The drift rate at each nominal pressure was determined by fitting a straight line to the four MIKES results. A summary of the drift rate results is presented in Table 1. Figures 2 and 3 illustrate the results on nominal pressures -95 kPa ***down*** and + 95 kPa ***up***.

The observed monthly drift at all nominal pressures was negligible compared to the uncertainty of the results. No drift corrections were made for the results. The time interval between the first comparison measurement at MIKES and last measurement at CMI was less than six weeks.

Table 1. The drift rate of the transfer standard at each nominal pressure calculated from the four calibrations at MIKES.

Nominal pressure kPa		Drift rate kPa/month	Average uncertainty kPa	Monthly drift / avg. unc.
0	down	0,00000	0,0012	0,00
-20	down	0,00000	0,0016	0,00
-40	down	-0,00009	0,0019	-0,05
-60	down	-0,00038	0,0023	-0,17
-80	down	0,00005	0,0026	0,02
-95	down	0,00067	0,0037	0,18
-95	up	-0,00017	0,0036	-0,05
-80	up	0,00012	0,0027	0,04
-60	up	0,00014	0,0022	0,06
-40	up	0,00003	0,0019	0,02
-20	up	0,00000	0,0020	0,00
0	up	0,00010	0,0013	0,08
0	up	0,00000	0,0012	0,00
20	up	0,00010	0,0016	0,06
40	up	0,00005	0,0019	0,03
60	up	0,00026	0,0022	0,12
80	up	0,00014	0,0026	0,05
95	up	0,00031	0,0030	0,10
95	down	-0,00007	0,0030	-0,02
80	down	0,00007	0,0026	0,03
60	down	0,00014	0,0022	0,06
40	down	0,00015	0,0019	0,08
20	down	-0,00013	0,0016	-0,08
0	down	0,00002	0,0013	0,02

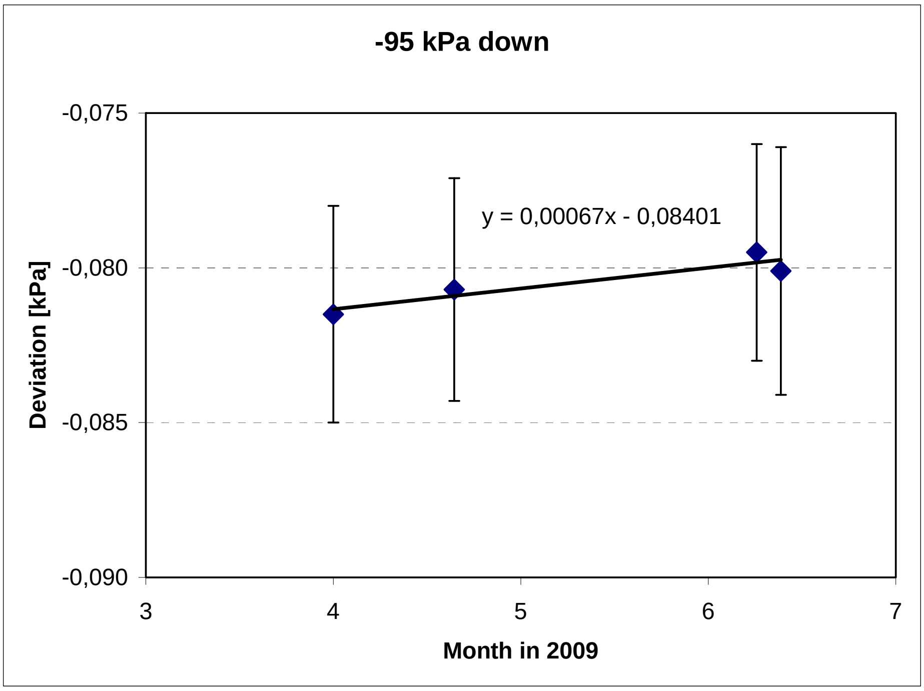

Figure 2. The drift rate of the transfer standard at -95 kPa down calculated from the four MIKES results. At other nominal pressures the drift rate was lower.

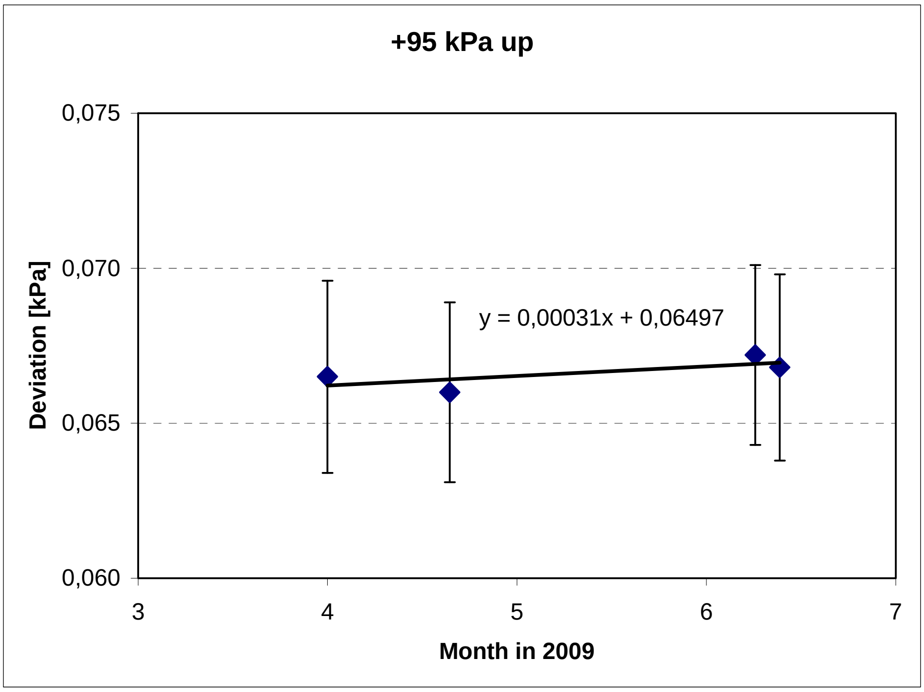

Figure 3. The drift rate of the transfer standard at +95 kPa up calculated from the four MIKES results.

7 Calculation of reference values

The reference values for the comparison were calculated following the guidelines of Ref. [3]. Applying Procedure A the weighted means of the results were calculated at each nominal pressure. As the pressures of Metrosert are traceable to MIKES, only the results from MIKES, FORCE Technology and CMI were included in calculations.

The weighted mean y of the results x at each nominal pressure was calculated as

$$y = \frac{x_1/u^2(x_1) + \cdots + x_N/u^2(x_N)}{1/u^2(x_1) + \cdots + 1/u^2(x_N)}$$

where x_i is the result and $u^2(x_i)$ the variance of the result from laboratory i.

The standard uncertainty $u(y)$ associated with y was calculated from

$$\frac{1}{u^2(y)} = \frac{1}{u^2(x_1)} + \cdots + \frac{1}{u^2(x_N)}$$

The consistency check specified in Procedure A of Ref. [3] using a chi squared test was carried out on all of the results. The results for nominal pressures -95 kPa ***down*** and -95 kPa ***up*** clearly failed the check, and they could not be accepted as reference values. All other results calculated as weighted means were accepted, despite some slightly exceeding chi squared –values.

The standard uncertainty $u(x_{ref})$ of the reference value x_{ref} was taken as

$$u(x_{ref}) = u(y)$$

and the expanded uncertainty $U(x_{ref})$

$$U(x_{ref}) = 2u(x_{ref}).$$

Procedure B of Ref. [3] was applied to the nominal pressures -95 kPa ***down*** and -95 kPa ***up***. The reference values were calculated as medians from the results of all four laboratories using Monte Carlo simulation with standard and expanded uncertainties accordingly.

The reference values for each nominal value and their uncertainties are presented in Table 2.

Table 2. Reference values for the comparison calculated as weighted means except for nominal pressures -95 kPa down and up as Monte Carlo simulated medians.

Nominal pressure kPa	Reference value kPa	Uncert. of ref. (k=2) kPa
0 down		
-20 down	-0,0127	0,0013
-40 down	-0,0279	0,0016
-60 down	-0,0431	0,0018
-80 down	-0,0609	0,0020
-95 down	-0,0837	0,0029
-95 up	-0,0834	0,0027
-80 up	-0,0631	0,0022
-60 up	-0,0474	0,0017
-40 up	-0,0319	0,0015
-20 up	-0,0154	0,0014
0 up		
0 up		
20 up	0,0154	0,0012
40 up	0,0296	0,0012
60 up	0,0423	0,0014
80 up	0,0571	0,0015
95 up	0,0671	0,0016
95 down	0,0682	0,0016
80 down	0,0591	0,0015
60 down	0,0453	0,0014
40 down	0,0325	0,0013
20 down	0,0178	0,0012
0 down		

The differences between weighted means and Monte Carlo simulated medians were small, as shown in Table 3.

Table 3. Weighted means and Monte Carlo simulated medians at nominal pressure -95 kPa.

Nominal pressure kPa	Weighted mean kPa	Uncertainty (k=2) kPa	Monte Carlo median kPa	Uncertainty (k=2) kPa
-95 down	-0,0827	0,0026	-0,0837	0,0029
-95 up	-0,0822	0,0026	-0,0834	0,0027

8 Results and equivalence with the reference values

Equivalence with the reference values

The results and their uncertainties as well as the deviations from the reference values are shown in Tables 4 - 7. The normalised error E_n - values are also included in the tables.

The deviation d_i of the laboratory result x_i from the reference value x_{ref} was calculated as

$$d_i = x_i - x_{ref} \; .$$

The standard uncertainty $u(d_i)$ of the deviation d_i from -20 kPa to -80 kPa ***down*** and ***up*** and all positive nominal pressures was calculated from

$$u^2(d_i) = u^2(x_i) - u^2(x_{ref})$$

and the expanded uncertainty $U(d_i)$ of the deviation d_i was calculated as

$$U(d_i) = 2u(d_i) \, .$$

At nominal pressures -95 kPa ***down*** and ***up*** the $U(d_i)$ values were generated by the Monte Carlo simulation.

The normalised error E_n - values were calculated as

$$E_n = d_i / U(d_i) \, .$$

A laboratory result is regarded as equivalent with the reference value if the E_n - value is between -1 and +1.

Figures 4 - 7 illustrate the results at nominal pressures -20 kPa ***down***, -95 kPa ***down***, +20 kPa ***up*** and +95 kPa ***up***. Figures 8 and 9 show a summary of the E_n - values.

Table 4. The results from Laboratory 1 (MIKES)

Nominal pressure kPa	Lab 1 result x_i kPa	Lab 1 unc. (k=2) $U(x_i)$ kPa	Reference value x_{ref} kPa	Uncert. of ref. (k=2) $U(x_{ref})$ kPa	Deviation from ref. d_i kPa	Uncert.of dev. (k=2) $U(d_i)$ kPa	E(n)
0 down	0,0000	0,0012					
-20 down	-0,0123	0,0019	-0,0127	0,0013	0,0004	0,0014	0,28
-40 down	-0,0277	0,0021	-0,0282	0,0017	0,0005	0,0013	0,36
-60 down	-0,0427	0,0023	-0,0434	0,0018	0,0007	0,0014	0,49
-80 down	-0,0609	0,0027	-0,0611	0,0020	0,0002	0,0018	0,11
-95 down	-0,0815	0,0036	-0,0837	0,0029	0,0022	0,0028	0,78
-95 up	-0,0809	0,0035	-0,0834	0,0027	0,0025	0,0027	0,94
-80 up	-0,0626	0,0028	-0,0634	0,0022	0,0008	0,0017	0,46
-60 up	-0,0474	0,0022	-0,0478	0,0018	0,0004	0,0013	0,27
-40 up	-0,0318	0,0019	-0,0318	0,0015	0,0000	0,0011	0,03
-20 up	-0,0150	0,0023	-0,0153	0,0014	0,0003	0,0018	0,18
0 up	-0,0023	0,0013					
0 up	0,0000	0,0012					
20 up	0,0153	0,0016	0,0156	0,0012	-0,0003	0,0011	-0,24
40 up	0,0301	0,0019	0,0297	0,0012	0,0004	0,0014	0,28
60 up	0,0424	0,0022	0,0425	0,0014	-0,0001	0,0017	-0,06
80 up	0,0566	0,0026	0,0572	0,0015	-0,0006	0,0021	-0,30
95 up	0,0665	0,0031	0,0673	0,0016	-0,0008	0,0027	-0,28
95 down	0,0675	0,0029	0,0683	0,0016	-0,0008	0,0024	-0,33
80 down	0,0586	0,0026	0,0592	0,0015	-0,0006	0,0021	-0,29
60 down	0,0454	0,0022	0,0455	0,0014	-0,0001	0,0017	-0,06
40 down	0,0331	0,0019	0,0327	0,0013	0,0004	0,0014	0,26
20 down	0,0180	0,0016	0,0179	0,0012	0,0001	0,0011	0,05
0 down	0,0024	0,0013					

Table 5. The results from Laboratory 2 (CMI)

Nominal pressure kPa	Lab 2 result x_i kPa	Lab 2 unc. (k=2) $U(x_i)$ kPa	Reference value x_{ref} kPa	Uncert. of ref. (k=2) $U(x_{ref})$ kPa	Deviation from ref. d_i kPa	Uncert.of dev. (k=2) $U(d_i)$ kPa	E(n)
0 down	0,000	0,002					
-20 down	-0,014	0,002	-0,0127	0,0013	-0,0013	0,0015	-0,85
-40 down	-0,030	0,003	-0,0282	0,0017	-0,0018	0,0025	-0,73
-60 down	-0,045	0,003	-0,0434	0,0018	-0,0016	0,0024	-0,66
-80 down	-0,062	0,003	-0,0611	0,0020	-0,0009	0,0023	-0,40
-95 down	-0,086	0,004	-0,0837	0,0029	-0,0023	0,0029	-0,81
-95 up	-0,086	0,004	-0,0834	0,0027	-0,0026	0,0027	-0,95
-80 up	-0,066	0,004	-0,0634	0,0022	-0,0026	0,0033	-0,79
-60 up	-0,049	0,003	-0,0478	0,0018	-0,0012	0,0025	-0,51
-40 up	-0,034	0,003	-0,0318	0,0015	-0,0022	0,0026	-0,84
-20 up	-0,016	0,002	-0,0153	0,0014	-0,0007	0,0014	-0,47
0 up	-0,002	0,002					
0 up	0,000	0,002					
20 up	0,016	0,002	0,0156	0,0012	0,0004	0,0016	0,28
40 up	0,030	0,002	0,0297	0,0012	0,0003	0,0016	0,20
60 up	0,043	0,002	0,0425	0,0014	0,0005	0,0014	0,34
80 up	0,058	0,002	0,0572	0,0015	0,0008	0,0013	0,59
95 up	0,068	0,002	0,0673	0,0016	0,0007	0,0012	0,62
95 down	0,069	0,002	0,0683	0,0016	0,0007	0,0012	0,56
80 down	0,060	0,002	0,0592	0,0015	0,0008	0,0013	0,59
60 down	0,046	0,002	0,0455	0,0014	0,0005	0,0014	0,34
40 down	0,033	0,002	0,0327	0,0013	0,0003	0,0016	0,17
20 down	0,018	0,002	0,0179	0,0012	0,0001	0,0016	0,03
0 down	0,001	0,002					

Table 6. The results from Laboratory 3 (FORCE Technology)

Nominal pressure kPa	Lab 3 result x_i kPa	Lab 3 unc. (k=2) $U(x_i)$ kPa	Reference value x_{ref} kPa	Uncert. of ref. (k=2) $U(x_{ref})$ kPa	Deviation from ref. d_i kPa	Uncert.of dev. (k=2) $U(d_i)$ kPa	E(n)
0 down	0,0000						
-20 down	-0,0099	0,0036	-0,0127	0,0013	0,0028	0,0034	0,83
-40 down	-0,0239	0,0065	-0,0282	0,0017	0,0043	0,0063	0,68
-60 down	-0,0379	0,0110	-0,0434	0,0018	0,0055	0,0109	0,51
-80 down	-0,0514	0,0115	-0,0611	0,0020	0,0097	0,0113	0,86
-95 down	-0,0682	0,0114	-0,0837	0,0029	0,0155	0,0099	***1,56***
-95 up	-0,0682	0,0114	-0,0834	0,0027	0,0152	0,0115	***1,32***
-80 up	-0,0544	0,0115	-0,0634	0,0022	0,0090	0,0113	0,79
-60 up	-0,0399	0,0110	-0,0478	0,0018	0,0079	0,0109	0,72
-40 up	-0,0269	0,0046	-0,0318	0,0015	0,0049	0,0043	***1,14***
-20 up	-0,0139	0,0037	-0,0153	0,0014	0,0014	0,0034	0,42
0 up	-0,0020						
0 up	0,0000						
20 up	0,0154	0,0037	0,0156	0,0012	-0,0002	0,0035	-0,04
40 up	0,0281	0,0029	0,0297	0,0012	-0,0016	0,0026	-0,61
60 up	0,0410	0,0038	0,0425	0,0014	-0,0015	0,0035	-0,42
80 up	0,0549	0,0048	0,0572	0,0015	-0,0023	0,0046	-0,51
95 up	0,0642	0,0053	0,0673	0,0016	-0,0031	0,0051	-0,60
95 down	0,0662	0,0052	0,0683	0,0016	-0,0021	0,0050	-0,42
80 down	0,0569	0,0047	0,0592	0,0015	-0,0023	0,0045	-0,52
60 down	0,0440	0,0038	0,0455	0,0014	-0,0015	0,0035	-0,42
40 down	0,0311	0,0031	0,0327	0,0013	-0,0016	0,0028	-0,58
20 down	0,0174	0,0040	0,0179	0,0012	-0,0005	0,0038	-0,14
0 down	0,0010						

Table 7. The results from Laboratory 4 (Metrosert)

Nominal pressure kPa	Lab 4 result x_i kPa	Lab 4 unc. (k=2) $U(x_i)$ kPa	Reference value x_{ref} kPa	Uncert. of ref. (k=2) $U(x_{ref})$ kPa	Deviation from ref. d_i kPa	Uncert.of dev. (k=2) $U(d_i)$ kPa	E(n)
0 down	0,000	0,001					
-20 down	-0,034	0,019	-0,0127	0,0013	-0,0213	0,0190	***-1,12***
-40 down	-0,052	0,021	-0,0282	0,0017	-0,0238	0,0209	***-1,14***
-60 down	-0,070	0,026	-0,0434	0,0018	-0,0266	0,0259	***-1,03***
-80 down	-0,089	0,027	-0,0611	0,0020	-0,0279	0,0269	***-1,04***
-95 down	-0,114	0,028	-0,0837	0,0029	-0,0303	0,0275	***-1,10***
-95 up	-0,122	0,031	-0,0834	0,0027	-0,0386	0,0306	***-1,26***
-80 up	-0,109	0,028	-0,0634	0,0022	-0,0456	0,0279	***-1,64***
-60 up	-0,098	0,026	-0,0478	0,0018	-0,0502	0,0259	***-1,94***
-40 up	-0,086	0,024	-0,0318	0,0015	-0,0542	0,0240	***-2,26***
-20 up	-0,075	0,031	-0,0153	0,0014	-0,0597	0,0310	***-1,93***
0 up	-0,002	0,002					
0 up	0,000	0,001					
20 up	0,014	0,003	0,0156	0,0012	-0,0016	0,0028	-0,56
40 up	0,027	0,003	0,0297	0,0012	-0,0027	0,0027	-0,99
60 up	0,039	0,004	0,0425	0,0014	-0,0035	0,0038	-0,93
80 up	0,051	0,005	0,0572	0,0015	-0,0062	0,0048	***-1,31***
95 up	0,061	0,006	0,0673	0,0016	-0,0063	0,0058	***-1,08***
95 down	0,062	0,006	0,0683	0,0016	-0,0063	0,0058	***-1,09***
80 down	0,054	0,005	0,0592	0,0015	-0,0052	0,0048	***-1,09***
60 down	0,041	0,003	0,0455	0,0014	-0,0045	0,0027	***-1,69***
40 down	0,030	0,003	0,0327	0,0013	-0,0027	0,0027	-1,00
20 down	0,016	0,002	0,0179	0,0012	-0,0019	0,0016	***-1,21***
0 down	0,001	0,002					

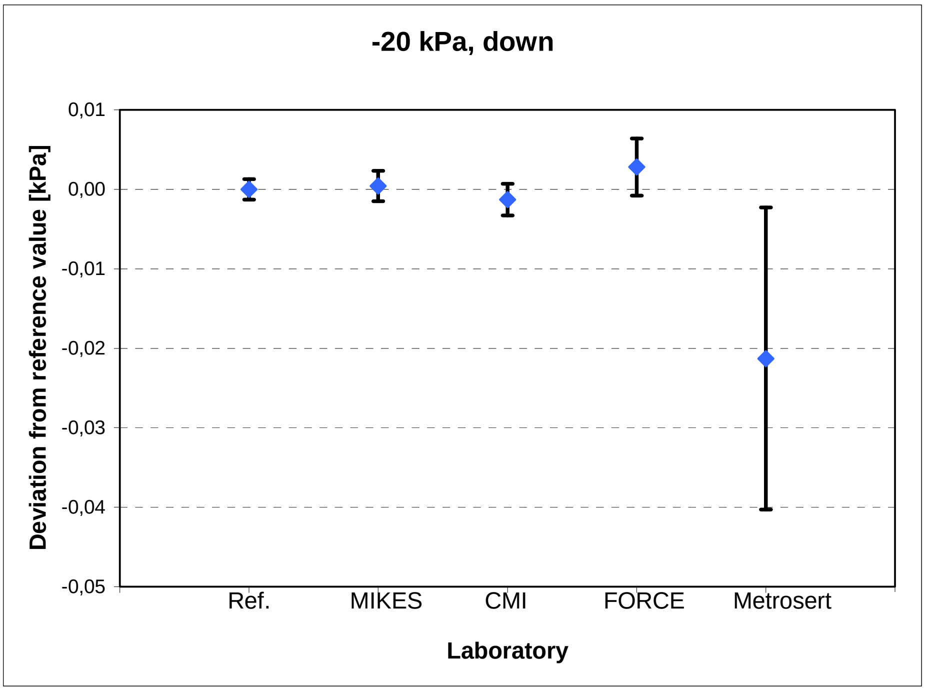

Figure 4. The results at nominal pressure -20 kPa down.

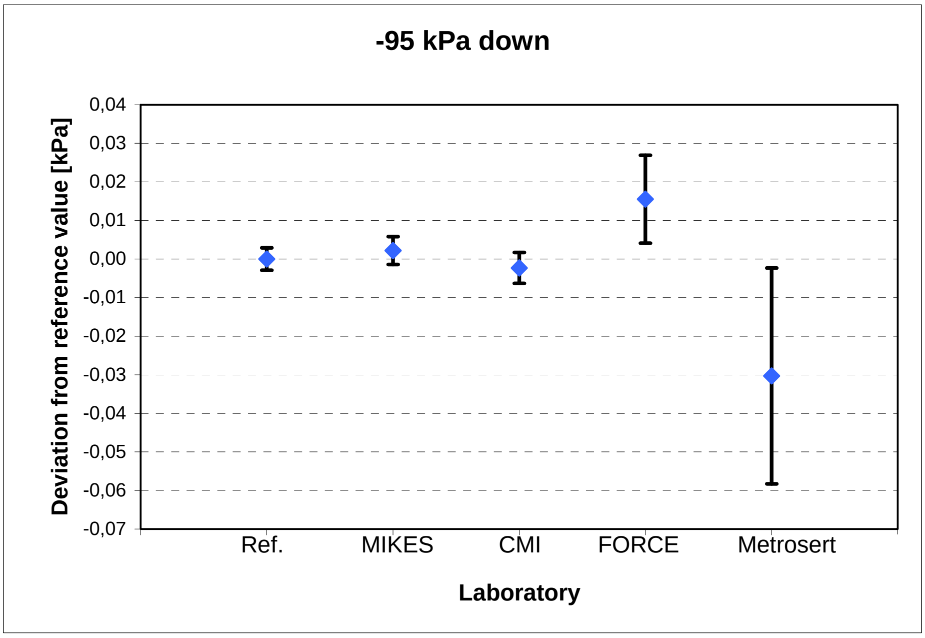

Figure 5. The results at nominal pressure -95 kPa down.

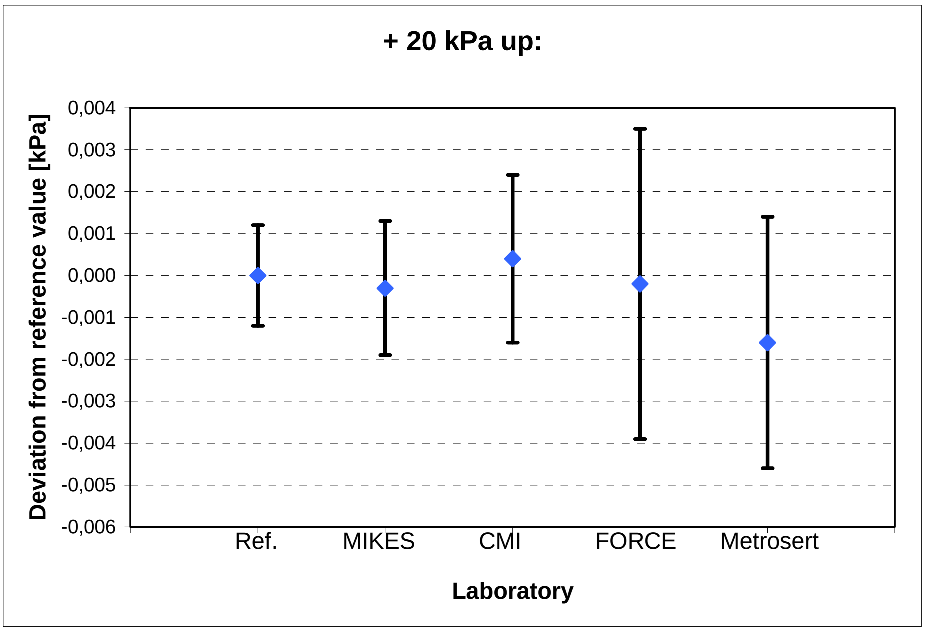

Figure 6. The results at nominal pressure +20 kPa up.

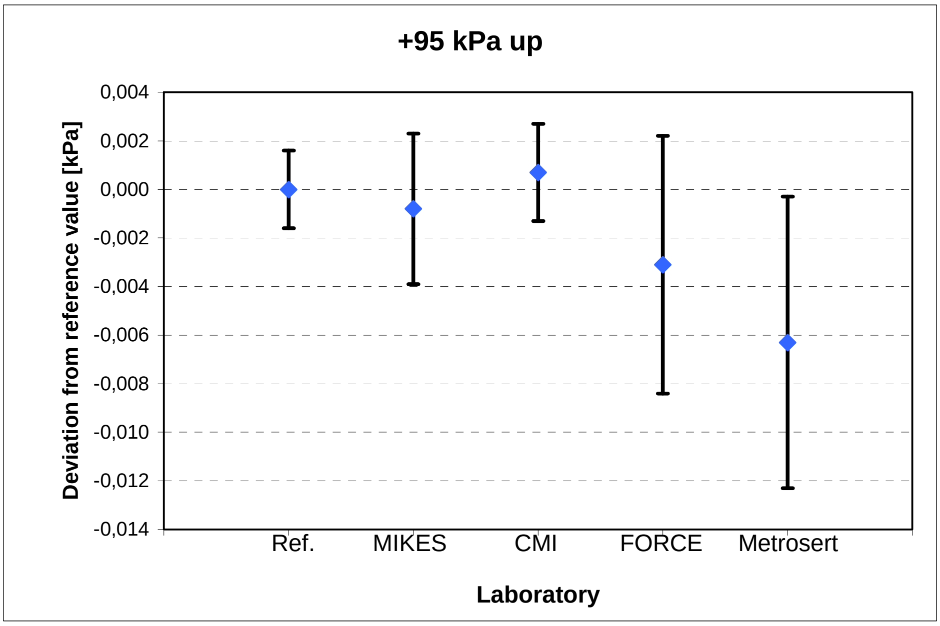

Figure 7. The results at nominal pressure +95 kPa up.

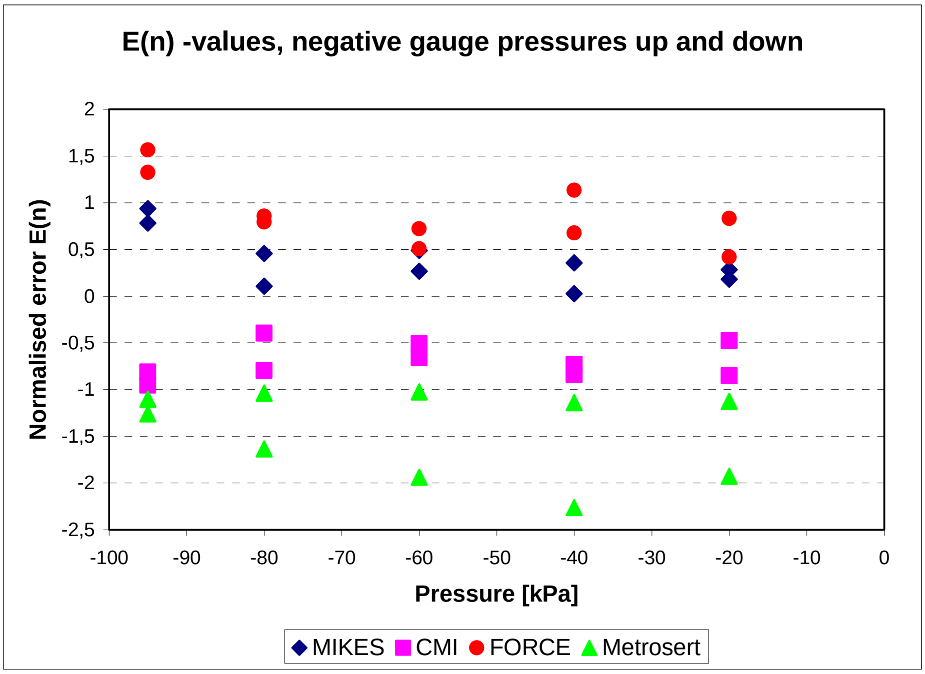

Figure 8. A summary of E_n - values at negative nominal pressures.

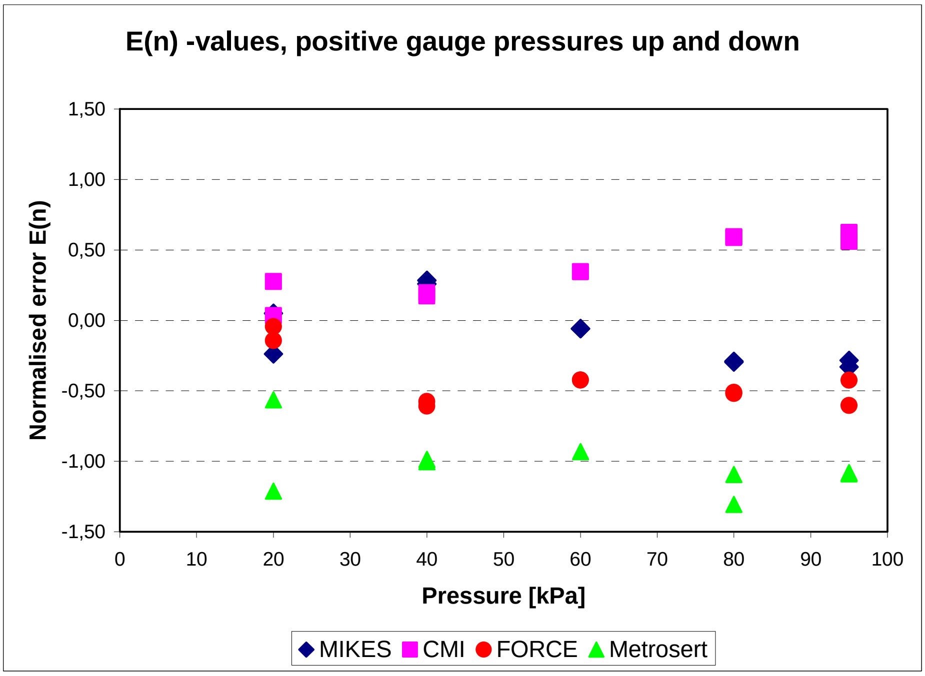

Figure 9. A summary of E_n - values at positive nominal pressures.

Mutual equivalence

The degree of the mutual equivalence of the results from each pair of laboratory results is expressed by two terms: the difference D_{ij} between the result x_i from laboratory i and the result x_j from laboratory j, and the uncertainty $U(D_{ij})$ of the difference. D_{ij} is defined as

$$D_{ij} = x_i - x_j$$

and

$$U(D_{ij}) = 2u(D_{ij})$$

where $u(D_{ij})$ is given by

$$u^2(D_{ij}) = u^2(x_i) + u^2(x_j) .$$

The results x_i and x_j are regarded as equivalent if $| D_{ij} | < U(D_{ij})$. The comparison of all results in pairs is shown in Appendix 2. A summary of non-equivalent result pairs between laboratories is given in Tables 8 and 9. All result pairs from MIKES and CMI were equivalent.

Table 8. Non-equivalent results pairs in negative pressure range.
Total number of result pairs = 10.

	MIKES	CMI	FORCE	Metrosert
MIKES	-	0	2	10
CMI	0	-	3	7
FORCE	2	3	-	10
Metrosert	10	7	10	-

Table 9. Non-equivalent results pairs in positive pressure range.
Total number of result pairs = 10.

	MIKES	CMI	FORCE	Metrosert
MIKES	-	0	0	1
CMI	0	-	0	5
FORCE	0	0	-	0
Metrosert	1	5	0	-

9 Comparison of the results to the best measurement capabilities

Figures 10 and 11 illustrate the uncertainties of the results claimed in this comparison by MIKES and CMI as well as their present CMC uncertainties in the BIPM database (October 2009).

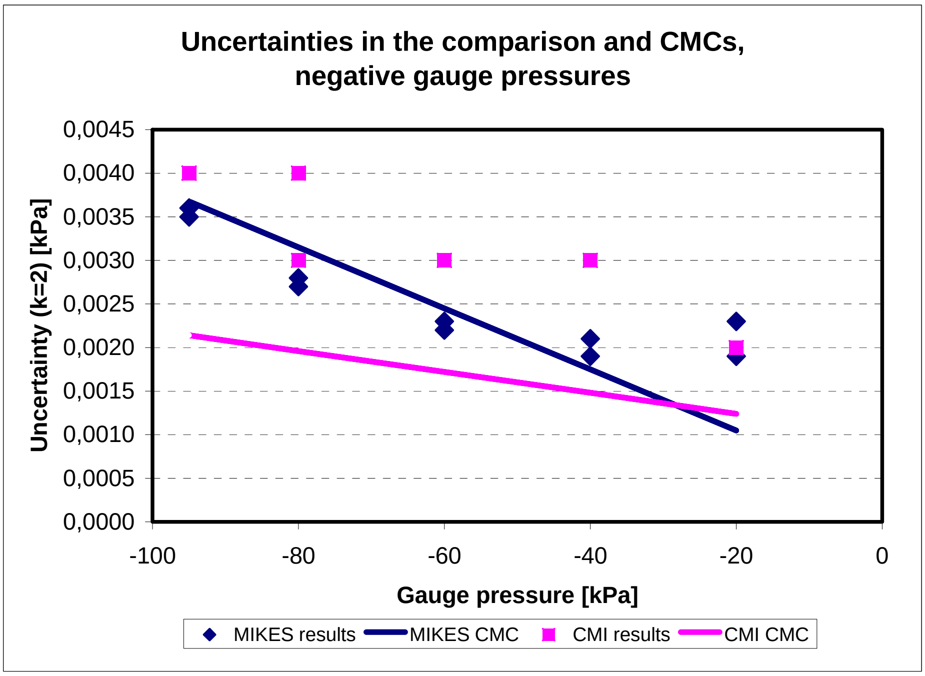

Fig. 10. Uncertainties from MIKES and CMI at negative gauge pressures.

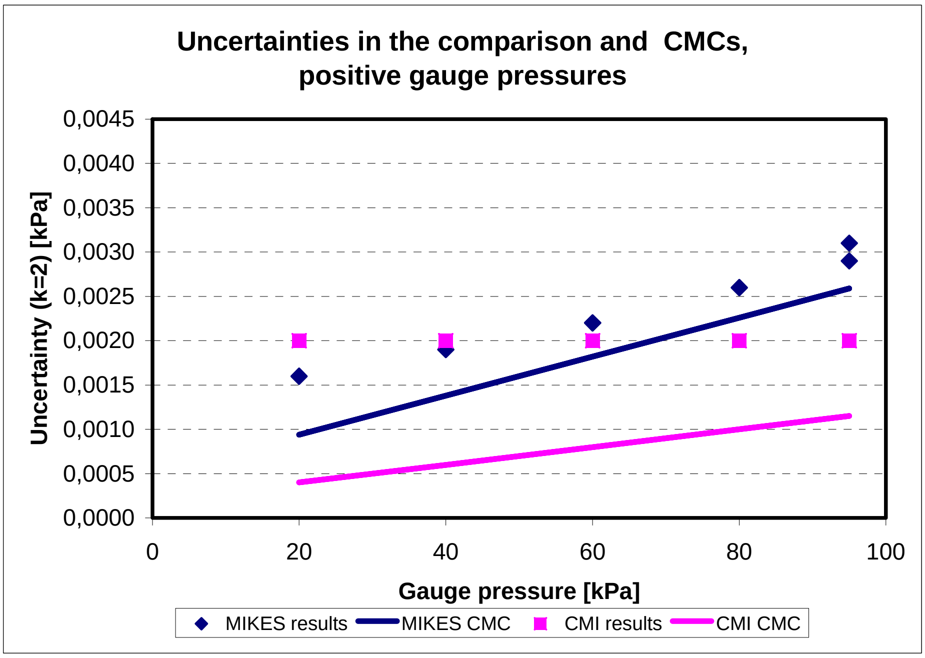

Fig. 11. Uncertainties from MIKES and CMI at positive gauge pressures.

The uncertainties given by MIKES for the comparison results on negative gauge pressures are approximately the same as the CMC uncertainties (Fig. 10).

The uncertainty values on negative gauge pressures from CMI, and on positive gauge pressures from CMI and MIKES do not give much support to the CMC uncertainties. Lower uncertainties could have been achieved with a better resolution of the transfer standard.

FORCE Technology and Metrosert have not included the negative gauge range of the present comparison in their CMC tables.

10 Conclusions

The results from the four participating laboratories suggest that the calibrations in the negative gauge pressure range are not as easy as expected. Some of the claimed uncertainties in the comparison were perhaps too optimistic, and the large variation in the results made it difficult to generate consistent reference values. The agreement of the results at positive gauge pressures for the same transfer standard was much better.

All results from CMI and MIKES were mutually equivalent.

Afterwards Metrosert announced that the sensitivity of their standard was not good during their measurements, leading to a large scatter in the results and probably also to deviating results. FORCE Technology has recalibrated their standard. Both would like to do their measurement again, but according to the BIPM key comparison rules this is not possible in the same comparison and on the same transfer standard.

Obviously there is a need for further comparisons in the negative gauge pressure range.

11 Acknowledgements

The authors wish to thank Mr. Pasi Kauppila of Oy Beamex Ab for providing the transfer standard, Dr. Wladimir Sabuga of PTB for his advice and help on the arrangements as well as for his comments on the report, and Dr. Kari Riski of MIKES for performing the Monte Carlo simulations.

12 References

[1] Rantanen, M., Semenoja, S.: Intercomparison in Gauge Pressure Range from -95 kPa to + 100 kPa. MIKES Publication J1/2006.

[2] Tesar, J., Krajicek, Z., Prazak, D., Stanek, F.: Primary etalonnage of negative gauge pressures using pressure balances at the Czech Metrology Institute. *Materiali in Tehnologie*. Vol. 43 (2009), No. 3, p. 151 - 156. ISSN 1580-2949.

[3] Cox, M. G.: The evaluation of key comparison data. Metrologia, 2002, 39, p. 589 - 595

Appendix 1: Measurement protocol

Negative gauge pressure comparison between CMI/CZ, FORCE/DK, Metrosert/EE and MIKES/FI

Measurement protocol, MR 22.4.2009

1. Introduction

Negative gauge pressures are a common range for pressure calibrations although uncertainty requirements in this range are not generally very high. As quality management systems in pressure calibration laboratories require inter-laboratory comparisons with a good coverage, CMI/CZ, MIKES/FI, FORCE Institute/DK and Metrosert/EE decided on a comparison in the negative gauge pressure range.

A high quality industrial pressure calibrator is available for the transfer standard, allowing the comparison of the laboratory performances in routine calibrations of both negative and positive gauge pressures. The comparison will be registered as a EURAMET project.

Negative gauge pressures have not been specified as a range needing key comparisons on the CCM or regional level.

2. Pilot laboratory

MIKES is responsible for preparing the measurement instructions, controlling the stability of the transfer standard and drafting the report.

3. Transfer standard

Beamex MC5 multifunction calibrator, serial No. 25516865, equipped with a INT1C pressure transducer for the nominal range -1 bar … + 1 bar, operating on clean air or nitrogen. A battery charger for 100 V … 240 V input is included, as well as a connector for flexible tubing and a ball valve.

The transfer standard was made available by the manufacturer Oy Beamex Ab, Pietarsaari, Finland.

4. Transportation

For transportation the instrument is packed in an aluminium case. Hand-carrying to the next participant is not necessary. A courier service or post can be used for transportation.

Please unpack the case immediately after delivery and inform the pilot laboratory about the arrival and the condition of the instrument.

Each participant is responsible for the costs of sending the instrument to the next laboratory.

5. Measurements

Preparation of the transfer standard

Plug in the battery charger. Place the instrument in a horizontal position, the display up. Switch the instrument on by pressing the red key. Press *Continue.* The pressure reading from the transducer is now shown in Window 1. Selecting *MENU* allows you to reselect *kPa* as the pressure unit if another unit is in use. The resolution of the display is 0,001 kPa when kPa is selected. Close the *MENU*.

Wait for at least 3 hours or preferably overnight before starting the measurement.

Measurements with negative gauge pressure

1. Select *MENU* and press *Zero Pressure Module*. Close the *MENU*.
2. Pre-pressurise two or three times to -95 kPa.
3. Wait for 3 to 5 minutes and zero the pressure module again at atmospheric pressure.
4. Feed the pressure from your laboratory standard to the transfer instrument and record the readings at nominal gauge pressures 0 kPa, -20 kPa, -40 kPa, -60 kPa, -80 kPa and -95 kPa. Do not come back to zero pressure between the points, if necessary use the attached ball valve to separate the transfer standard when preparing the next nominal pressure.
5. Apply pressure -98 kPa ± 2 kPa for approximately 2 minutes.
6. Feed the pressure from your laboratory standard to the transfer instrument and record the readings at nominal gauge pressures -95 kPa, -80 kPa, -60 kPa, -40 kPa, -20 kPa and 0 kPa. (The results in increasing and decreasing direction of pressure will be treated separately to minimise hysteresis effects).
7. Wait for 3 to 5 minutes with the pressure module at atmospheric pressure and zero the pressure module again.
8. Repeat the steps 4 to 6 at least two times to get at least three results at each nominal pressure both with increasing and decreasing pressures.

Measurements with positive gauge pressure

1. Wait at least 10 minutes after measurements with negative gauge pressures.
2. Pre-pressurise two or three times to +95 kPa.
3. Wait for 3 to 5 minutes and zero the pressure module again at atmospheric pressure.
4. Feed the pressure from your laboratory standard to the transfer instrument and record the readings at nominal gauge pressures 0 kPa, +20 kPa, +40 kPa, +60 kPa, +80 kPa and +95 kPa.
5. Apply pressure +98 kPa ± 2 kPa for approximately 2 minutes.
6. Feed the pressure from your laboratory standard to the transfer instrument and record the readings at nominal gauge pressures +95 kPa, +80 kPa, +60 kPa, +40 kPa, +20 kPa and 0 kPa. (The results in increasing and decreasing direction of pressure are treated separately to minimise hysteresis effects).
7. Wait for 3 to 5 minutes with the pressure module at atmospheric pressure and zero the pressure module again.
8. Repeat the steps 4 to 6 at least two times to get at least three results at each nominal pressure both with increasing and decreasing pressures.

Do not make any other adjustments on the device before or after your measurements.

6. Circulation scheme

Laboratory	Scheduled time
MIKES 1st	Week 14
MIKES 2nd	Week 17
Metrosert	Week 18
FORCE Technology Brøndby	Week 19
CMI	Week 20
MIKES 3rd	Week 21
MIKES 4th	Week 22

The measurements in MIKES will be repeated four times to check the stability of the transfer standard. The results from the second measurement will be taken in the comparison.

7. Report

The minimum content of the results to be delivered is:

- Deviation of the transfer standard reading from the laboratory standard at each nominal pressure + the uncertainty (k=2) of the deviation
- Description of the laboratory standard and its traceability
- Reference to the certificate of calibration, in case more detailed information of the measurements is needed.

Each participant will send the results within two weeks of the measurement to

Dr. Wladimir Sabuga
Physikalisch-Technische Bundesanstalt (PTB)
Leiter der Arbeitsgruppe 3.33 "Druck"
Bundesallee 100
D-38116 Braunschweig
Germany
e-mail: wladimir.sabuga@ptb.de

Dr. Sabuga promised to act as a third party and collect the results for maximum confidence on the comparison. He will then send all the results to the pilot laboratory.

The pilot laboratory will draft the report and send it for comments to all participants.

List of participating laboratories:

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AS Metrosert
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Estonia

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Centre for Metrology and Accreditation (MIKES)
P.O. Box 9 (Tekniikantie 1)
FI – 02151 ESPOO
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Contact persons: Markku Rantanen	Sari Saxholm
Phone number: +358 10 6054 428	+358 10 6054 432
Fax: +358 10 6054 499	+358 10 6054 499
Email: markku.rantanen@mikes.fi	sari.saxholm@mikes.fi

Transfer standard in its case

Appendix 2. Results of mutual equivalence

APPENDIX 2a. Mutual equivalence of the results at negative nominal pressures, decreasing direction.

-20 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0123	0,0019			0,0017	0,0028	-0,0024	0,0041	***0,0217***	***0,0191***
CMI	-0,0140	0,0020	-0,0017	0,0028			-0,0041	0,0041	***0,0200***	***0,0191***
FORCE	-0,0099	0,0036	0,0024	0,0041	0,0041	0,0041			***0,0241***	***0,0193***
Metrosert	-0,0340	0,0190	***-0,0217***	***0,0191***	***-0,0200***	***0,0191***	***-0,0241***	***0,0193***		

-40 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0277	0,0021			0,0023	0,0037	-0,0038	0,0068	***0,0243***	***0,0211***
CMI	-0,0300	0,0030	-0,0023	0,0037			-0,0061	0,0072	***0,0220***	***0,0212***
FORCE	-0,0239	0,0065	0,0038	0,0068	0,0061	0,0072			***0,0281***	***0,0220***
Metrosert	-0,0520	0,0210	***-0,0243***	***0,0211***	***-0,0220***	***0,0212***	***-0,0281***	***0,0220***		

-60 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0427	0,0023			0,0023	0,0038	-0,0048	0,0112	***0,0273***	***0,0261***
CMI	-0,0450	0,0030	-0,0023	0,0038			-0,0071	0,0114	0,0250	0,0262
FORCE	-0,0379	0,0110	0,0048	0,0112	0,0071	0,0114			***0,0321***	***0,0282***
Metrosert	-0,0700	0,0260	***-0,0273***	***0,0261***	-0,0250	0,0262	***-0,0321***	***0,0282***		

-80 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0609	0,0027			0,0011	0,0040	-0,0095	0,0118	***0,0281***	***0,0271***
CMI	-0,0620	0,0030	-0,0011	0,0040			-0,0106	0,0119	0,0270	0,0272
FORCE	-0,0514	0,0115	0,0095	0,0118	0,0106	0,0119			***0,0376***	***0,0293***
Metrosert	-0,0890	0,0270	***-0,0281***	***0,0271***	-0,0270	0,0272	***-0,0376***	***0,0293***		

-95 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0815	0,0036			0,0045	0,0054	***-0,0133***	***0,0120***	***0,0325***	***0,0282***
CMI	-0,0860	0,0040	-0,0045	0,0054			***-0,0178***	***0,0121***	0,0280	0,0283
FORCE	-0,0682	0,0114	***0,0133***	***0,0120***	***0,0178***	***0,0121***			***0,0458***	***0,0302***
Metrosert	-0,1140	0,0280	***-0,0325***	***0,0282***	-0,0280	0,0283	***-0,0458***	***0,0302***		

APPENDIX 2b. Mutual equivalence of the results at negative nominal pressures, increasing direction.

-95 kPa u		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0809	0,0035			0,0051	0,0053	***-0,0127***	***0,0119***	***0,0411***	***0,0312***
CMI	-0,0860	0,0040	-0,0051	0,0053			***-0,0178***	***0,0121***	***0,0360***	***0,0313***
FORCE	-0,0682	0,0114	***0,0127***	***0,0119***	***0,0178***	***0,0121***			***0,0538***	***0,0330***
Metrosert	-0,1220	0,0310	***-0,0411***	***0,0312***	***-0,0360***	***0,0313***	***-0,0538***	***0,0330***		

-80 kPa u		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0626	0,0028			0,0034	0,0049	-0,0082	0,0118	***0,0464***	***0,0281***
CMI	-0,0660	0,0040	-0,0034	0,0049			-0,0116	0,0122	***0,0430***	***0,0283***
FORCE	-0,0544	0,0115	0,0082	0,0118	0,0116	0,0122			***0,0546***	***0,0303***
Metrosert	-0,1090	0,0280	***-0,0464***	***0,0281***	***-0,0430***	***0,0283***	***-0,0546***	***0,0303***		

-60 kPa u		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0474	0,0022			0,0016	0,0037	-0,0075	0,0112	0,0506	0,0261
CMI	-0,0490	0,0030	-0,0016	0,0037			-0,0091	0,0114	0,0490	0,0262
FORCE	-0,0399	0,0110	0,0075	0,0112	0,0091	0,0114			***0,0581***	***0,0282***
Metrosert	-0,0980	0,0260	-0,0506	0,0261	-0,0490	0,0262	***-0,0581***	***0,0282***		

-40 kPa u		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0318	0,0019			0,0022	0,0036	-0,0049	0,0050	***0,0542***	***0,0241***
CMI	-0,0340	0,0030	-0,0022	0,0036			***-0,0071***	***0,0055***	***0,0520***	***0,0242***
FORCE	-0,0269	0,0046	0,0049	0,0050	***0,0071***	***0,0055***			***0,0591***	***0,0244***
Metrosert	-0,0860	0,0240	***-0,0542***	***0,0241***	***-0,0520***	***0,0242***	***-0,0591***	***0,0244***		

-20 kPa u		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	-0,0150	0,0023			0,0010	0,0030	-0,0011	0,0044	***0,0600***	***0,0311***
CMI	-0,0160	0,0020	-0,0010	0,0030			-0,0021	0,0042	***0,0590***	***0,0311***
FORCE	-0,0139	0,0037	0,0011	0,0044	0,0021	0,0042			***0,0611***	***0,0312***
Metrosert	-0,0750	0,0310	**-0,0600**	**0,0311**	***-0,0590***	***0,0311***	***-0,0611***	***0,0312***		

APPENDIX 2c. Mutual equivalence of the results at positive nominal pressures, increasing direction.

20 kPa u		**Lab j**	**MIKES**		**CMI**		**FORCE**		**Metrosert**	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0153	0,0016			-0,0007	0,0026	-0,0001	0,0035	0,0013	0,0034
CMI	0,0160	0,0020	0,0007	0,0026			0,0006	0,0037	0,0020	0,0036
FORCE	0,0154	0,0031	0,0001	0,0035	-0,0006	0,0037			0,0014	0,0043
Metrosert	0,0140	0,0030	-0,0013	0,0034	-0,0020	0,0036	-0,0014	0,0043		

40 kPa u		**Lab j**	**MIKES**		**CMI**		**FORCE**		**Metrosert**	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0301	0,0019			0,0001	0,0028	0,0020	0,0042	0,0031	0,0036
CMI	0,0300	0,0020	-0,0001	0,0028			0,0019	0,0042	0,0030	0,0036
FORCE	0,0281	0,0037	-0,0020	0,0042	-0,0019	0,0042			0,0011	0,0048
Metrosert	0,0270	0,0030	-0,0031	0,0036	-0,0030	0,0036	-0,0011	0,0048		

60 kPa u		**Lab j**	**MIKES**		**CMI**		**FORCE**		**Metrosert**	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0424	0,0022			-0,0006	0,0030	0,0014	0,0044	0,0034	0,0046
CMI	0,0430	0,0020	0,0006	0,0030			0,0020	0,0043	0,0040	0,0045
FORCE	0,0410	0,0038	-0,0014	0,0044	-0,0020	0,0043			0,0020	0,0055
Metrosert	0,0390	0,0040	-0,0034	0,0046	-0,0040	0,0045	-0,0020	0,0055		

80 kPa u		**Lab j**	**MIKES**		**CMI**		**FORCE**		**Metrosert**	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0566	0,0026			-0,0014	0,0033	0,0017	0,0055	0,0056	0,0056
CMI	0,0580	0,0020	0,0014	0,0033			0,0031	0,0052	***0,0070***	***0,0054***
FORCE	0,0549	0,0048	-0,0017	0,0055	-0,0031	0,0052			0,0039	0,0069
Metrosert	0,0510	0,0050	-0,0056	0,0056	***-0,0070***	***0,0054***	-0,0039	0,0069		

95 kPa u		**Lab j**	**MIKES**		**CMI**		**FORCE**		**Metrosert**	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0665	0,0031			-0,0015	0,0037	0,0023	0,0061	0,0055	0,0068
CMI	0,0680	0,0020	0,0015	0,0037			0,0038	0,0057	***0,0070***	***0,0063***
FORCE	0,0642	0,0053	-0,0023	0,0061	-0,0038	0,0057			0,0032	0,0080
Metrosert	0,0610	0,0060	-0,0055	0,0068	***-0,0070***	***0,0063***	-0,0032	0,0080		

APPENDIX 2d. Mutual equivalence of the results at positive nominal pressures, decreasing direction.

95 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0675	0,0029			-0,0015	0,0035	0,0013	0,0060	0,0055	0,0067
CMI	0,0690	0,0020	0,0015	0,0035			0,0028	0,0056	***0,0070***	***0,0063***
FORCE	0,0662	0,0052	-0,0013	0,0060	-0,0028	0,0056			0,0042	0,0079
Metrosert	0,0620	0,0060	-0,0055	0,0067	***-0,0070***	***0,0063***	-0,0042	0,0079		

80 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0586	0,0026			0,0006	0,0033	0,0017	0,0054	0,0046	0,0056
CMI	0,0580	0,0020	-0,0006	0,0033			0,0011	0,0051	0,0040	0,0054
FORCE	0,0569	0,0047	-0,0017	0,0054	-0,0011	0,0051			0,0029	0,0069
Metrosert	0,0540	0,0050	-0,0046	0,0056	-0,0040	0,0054	-0,0029	0,0069		

60 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0454	0,0022			-0,0006	0,0030	0,0014	0,0044	***0,0044***	***0,0037***
CMI	0,0460	0,0020	0,0006	0,0030			0,0020	0,0043	***0,0050***	***0,0036***
FORCE	0,0440	0,0038	-0,0014	0,0044	-0,0020	0,0043			0,0030	0,0048
Metrosert	0,0410	0,0030	***-0,0044***	***0,0037***	***-0,0050***	***0,0036***	-0,0030	0,0048		

40 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0331	0,0019			0,0001	0,0028	0,0020	0,0036	0,0031	0,0036
CMI	0,0330	0,0020	-0,0001	0,0028			0,0019	0,0037	0,0030	0,0036
FORCE	0,0311	0,0031	-0,0020	0,0036	-0,0019	0,0037			0,0011	0,0043
Metrosert	0,0300	0,0030	-0,0031	0,0036	-0,0030	0,0036	-0,0011	0,0043		

20 kPa d		Lab j	MIKES		CMI		FORCE		Metrosert	
	x_i	$U(x_i)$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
MIKES	0,0180	0,0016			0,0000	0,0026	0,0006	0,0043	0,0020	0,0026
CMI	0,0180	0,0020	0,0000	0,0026			0,0006	0,0045	0,0020	0,0028
FORCE	0,0174	0,0040	-0,0006	0,0043	-0,0006	0,0045			0,0014	0,0045
Metrosert	0,0160	0,0020	-0,0020	0,0026	-0,0020	0,0028	-0,0014	0,0045		

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