metrologia

Comparison of pressure standards in the range 10 kPa to 140 kPa

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Abstract. This report summarizes the results obtained by twelve laboratories in a comparison of pressure measurement standards in the range 10 kPa to 140 kPa, carried out under the auspices of the Consultative Committee for Mass and Related Quantities. Measurements were taken in the absolute mode and, by some participants, in the gauge mode. Good repeatability and, until near the end, reproducibility were observed in the transfer standard. The results displayed significant differences between some of the participants beyond those expected from their claimed uncertainties.

1. Introduction

The comparison described in this report was organized by the Medium-Pressure Working Group of the Consultative Committee for Mass and Related Quantities (CCM).

The pressure range from 10 kPa to 140 kPa is of importance in, for example, atmospheric-pressure measurement (to meet the requirements of aviation altimetry and meteorology), gas thermometry, buoyancy corrections in weighing, refractive-index corrections in length metrology and air-absorption corrections in the measurement of ionizing radiation. The medium-pressure range is also frequently used to provide traceability to both higher and lower pressures by stepping-up or stepping-down procedures.

The comparison was organized on a "petal" basis, with the transfer standard returning periodically to the pilot laboratory (National Physical Laboratory, UK) for checking. A progress report on this comparison has already been described by Stuart [1]. The complete list of laboratories which took part is, in order of participation:

- National Physical Laboratory (NPL), UK;
- Bureau International des Poids et Mesures (BIPM), France;
- Institut National de Métrologie (INM), France;
- Slovak Institute of Metrology (SIM), Slovakia (formerly CSMU, Czechoslovakia);
- Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia;
- National Institute of Standards and Technology (NIST), USA (formerly NBS, USA);
- National Research Laboratory of Metrology (NRLM), Japan;
- Physikalisch-Technische Bundesanstalt, Friedrichshagen (PTB(F)), Germany (formerly ASMW, GDR);
- Physikalisch-Technische Bundesanstalt, Braunschweig (PTB(B)), Germany;
- Consiglio Nazionale delle Ricerche, Istituto di Metrologia "G. Colonnetti" (IMGC), Italy;
- National Research Council (NRC), Canada;
- National Physical Laboratory (NPL), India.

Both the NIST and the IMGC took measurements using more than one standard, while the BIPM took part twice.

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All laboratories took measurements in the absolute mode, with the NIST, NRLM, PTB(F), IMGC and NRC also taking measurements in the gauge mode.

The interval between the first and last measurements for this comparison was twelve years. During such a timescale – and indeed sometimes after much shorter comparisons – measurement standards are often modified to some degree. Thus results tend to represent performance as it was, and not necessarily as it is, and Section 8 summarizes the modifications made by some participants during or after the exercise.

2. Transfer standard

The transfer standard used in the comparison was a specially modified gas-operated pressure balance: the CEC piston-cylinder was supplied by the NIST and the base by the CSIRO. The modifications increased the vacuum-pumping path, allowed more accurate temperature measurement of the piston-cylinder assembly, and allowed weights to be changed without removing the bell-jar. These greatly reduced the time between observations and led to improved residual pressures when operating in the absolute mode. A further modification was to mount the piston drive motor outside the vacuum enclosure in order to reduce any heating effects. To minimize piston wear the rotational drive torque was applied by a symmetrical belt-drive, rather than by a single, tangential, drive. The system was circulated with six ring weights and one bias weight, enabling pressures in the range 11 kPa to 141 kPa to be generated.

As pilot laboratory, the NPL provided a calibrated thermometer and Pirani gauge, calibration of the weights, periodic redetermination of the transfer standard effective area and reduction and organization of the results.

3. Description of participants' measurement standards

3.1 National Physical Laboratory (UK)

The NPL standard used for the comparison was a barometer in which the levels of the mercury surfaces were measured interferometrically using a helium-neon laser. It was used solely in the absolute mode. "Cat's-eye" floats enabled height measurements to be made directly to the mercury surfaces while tolerating surface ripples [2]. The internal diameter of the U-tube was 110 mm and the temperatures of the surrounding water jackets were measured with platinum resistance thermometers. The mercury in the barometer was taken from one of the samples whose density was measured by Cook and Stone [3, 4].

3.2 Bureau International des Poids et Mesures

The standard employed by the BIPM was a white-light Michelson interferometer mercury manometer, working in the absolute mode only, over the range 11 kPa to 101 kPa.

3.3 Institut National de Métrologie

The INM standard [5], used for absolute measurements only, consisted of two 115 mm diameter, mercury-filled cells connected via a flexible tube. One of these two cells was fixed and the other movable in the vertical axis. Initially, the mercury in the cells was set at the same height and the cells evacuated. A pressure was then applied to the fixed cell causing movement in the mercury level. The mercury levels in the two cells, measured using capacitive bridge detectors, were then adjusted to return them to their original levels by vertical displacement of the movable cell. This displacement, measured using laser interferometry, was therefore equal to the height of the mercury column. The operating range of the manometer was 0 kPa to 108 kPa.

3.4 Slovak Institute of Metrology

The SMU standard [6] was a mercury manometer in which the columns were in the form of two concentric tubes. It was used for absolute measurements only. The diameter of the external tube was significantly wider at the top (170 mm diameter) so as to minimize meniscus effects. The diameter of the inner tube was 70 mm. The mercury in the outer reference column was maintained at a constant level while the vertical displacement of the mercury in the inner, measuring column, was tracked by a disk capacitance sensor, located on the bottom of a sealed movable piston driven by a lead screw. Changes in the height of the capacitance sensor, and thus the mercury surface, were measured using a Michelson interferometer in which one beam was reflected by a cube-corner mounted in the bottom of the piston.

3.5 Commonwealth Scientific and Industrial Research Organization

The CSIRO standard [7] consisted of a mercury-filled U-tube manometer in which the mercury surfaces acted as the reflectors of a Michelson interferometer. The difference in heights of the mercury surfaces was measured by use of laser interferometry techniques using a He-Ne laser. "Cat's-eye" floats enabled height measurements to be made directly to the mercury surfaces while tolerating surface ripples. This standard was used only in the absolute mode.

3.6 National Institute of Standards and Technology

The NIST used two standards in the comparison. For the purposes of this report, they are referred to as NIST1 and NIST2.

NIST1 was used for measurements in both the absolute and gauge modes. The standard was a mercury manometer employing an ultrasonic technique to measure the lengths of the mercury columns, the change in lengths being detected from the change in phase of an ultrasonic wave propagated through the mercury and reflected from the mercury-gas interface [8]. The mercury columns were of 75 mm diameter and located within a temperature-lagged enclosure.

NIST2 was a commercially available piston-cylinder which had been modified in several ways [9]. The entire mechanism for the top and bottom stops had been replaced with parts made from Kel-F to ease cleaning and eliminate a source of dirt. The rotative mechanism had been modified so that the cylinder, piston and weight stack were rotated together before the piston was floated, the cylinder stopped and the piston allowed to continue. In addition, a conductive film had been added to the bottom stop to prevent the build-up of an electrostatic charge when the weight carrier rubbed on it. The piston-cylinder had been calibrated by reference to a gas thermometer manometer [10].

3.7 National Research Laboratory of Metrology

The NRLM standard [11] was a mercury U-tube manometer used for measurements in both the absolute and gauge modes. The positions of the mercury surfaces were measured using two white-light Michelson interferometers whose reference mirrors were movable corner cubes, the positions of which were measured using laser interferometry. The corner cubes were positioned in chambers whose conditions were controlled to be the same as in the U-tube to prevent any errors caused by differences in refractive index.

3.8 Physikalisch-Technische Bundesanstalt (F)

The PTB(F) standard [12], part of the former ASMW at the time these data were taken, was used in both the absolute and gauge modes. The standard was a dual-cistern mercury manometer in which the mercury surfaces were detected using capacitance sensing. Pressure was applied to one of the cisterns which was mounted on a dual-carriage system allowing fine adjustment of its height over the full range (850 mm) of the manometer. The reference pressure was applied to the other, fixed, cistern. The cisterns were connected via two rigid vertical tubes and a length of flexible tubing. The mercury surfaces were adjusted to a fixed position below each capacitance sensor using a precise volume displacer, and the vertical displacement of the movable cistern measured on a vertical glass scale using a spiral microscope.

3.9 Physikalisch-Technische Bundesanstalt (B)

The PTB(B) standard [13], used solely in the absolute mode, was a modified commercially available dual-cistern mercury manometer. Improved temperature control was obtained by removing its side walls and siting it within a thermally isolated chamber. The movement of the mercury cisterns was measured interferometrically and the position of the mercury surfaces within the cisterns measured using a capacitance bridge connected to a sensitive compensation recorder, allowing the movable cistern to be positioned within ± 0.1 µm. Other modifications to the original design included the replacement of a vacuum line by a piece of flexible tubing and the use of a capacitance manometer situated above the capacitor plate in the movable cistern to measure the residual pressure.

3.10 Istituto di Metrologia "G. Colonnetti"

The IMGC used three standards in the comparison. For the purposes of this paper, they are referred to as IMGC1, IMGC2 and IMGC3.

IMGC1 [14] was used solely for measurements in the gauge mode. The standard consisted of a pressure balance containing a tungsten-carbide piston-cylinder with an effective area of nominally 336 mm^2 and an operating range of 6.4 kPa to 137 kPa. Traceability for its effective area had been obtained from both dimensional measurements and comparison with IMGC mercury manometers.

IMGC2 [15] was used for both absolute and gauge mode measurements over the range 0 kPa to 120 kPa. It consisted of a mercury-filled U-tube, whose limbs were 50 mm diameter glass tubes, 1 m in length, connected via a stainless-steel base. The heights of its mercury surfaces were measured interferometrically, the beams being reflected from cube-corner retroreflectors supported on the mercury by very lightweight floats.

The IMGC3 standard [16] was used for measurements solely in the absolute mode, over the range 11 kPa to 101 kPa. This standard was a mercury column manometer whose column heights were measured using white-light interferometry.

3.11 National Research Council (Canada)

The NRC standard used for both absolute and gauge mode measurements was a Schwien mercury manometer. The manometer had been modified at the NRC to include a laser interferometer to measure the height of the mercury column and a high-accuracy capacitance gauge to measure the reference pressure. Also, to improve the temperature stability along the mercury column, the manometer was separated from the electronics panel and housed in a thermally isolated chamber. The mercury column in the manometer was contained within a flexible steel tube, each end of which terminated in a 3 inch (7.6 cm) diameter cistern. One cistern was fixed and the other was movable. The mercury-column height within the flexible mercury line was established by elevating the moving cistern whose displacement was measured using the laser interferometer. The level of mercury in each cistern was maintained constant by using a high-accuracy capacitance gauging system.

3.12 National Physical Laboratory (India)

The standard employed by the NPL (India) was an Ultrasonic Interferometer Manometer (UIM), developed in cooperation with the NIST [8]. It consisted of a W-tube manometer, operating over the range 1 Pa to 130 kPa in the absolute mode, with its surface positions sensed by ultrasonic wavechains. The height difference was thus measured in terms of the wavelength of sound in mercury.

4. Calibration procedure

Each participant measured the pressures required to support the piston of the transfer standard when it was loaded with specified combinations of weights. The minimum load was supported by a pressure of approximately 11 kPa, with six ring weights providing pressure increments of approximately 20 kPa. A bias weight of approximately half the mass of the others enabled the generation of seven interleaved pressures up to a maximum of approximately 141 kPa. Not all participants, however, were able to take measurements across the whole range, particularly at the higher pressures.

Observations were made, first without the bias weight, for both ascending and descending pressure sequences and for both clockwise and anticlockwise rotations. Thus there were four observations at each pressure in the cycle, which was then repeated, making a total of eight observations at each pressure. This sequence was then repeated with the bias weight loaded.

5. Treatment of data

For each ring-weight combination, participants were required to calculate the mean value and standard deviation of the pressure at the datum level of the transfer standard corrected to 20 °C and standard gravity. The mean calculated generated pressure is given by

$$P_\mathrm{c} = (9.806\,65/\mathrm{g}) \left[\sum_{i=1}^{n} C\,D \right] / n$$

$$C = \left[P_\mathrm{m} \left(1 - \frac{0.0034\,gh}{\mathrm{t_a} + 273.15} \right) - P_\mathrm{r} \right]$$

$$D = [1 + \alpha\,(t_\mathrm{c} - 20)],$$

where

- i = measurement number;
- P_c = mean calculated generated pressure (Pa);
- g = local value of gravitational acceleration (m s^{-2});
- n = number of measurements by the participant;
- P_m = pressure measured at the reference level of the participant's standard (Pa);
- h = the amount by which the height of the reference level of the transfer standard was above the height of the reference level of the participant's standard (m);
- t_a = the mean temperature of any vertical parts of the pipe connecting the two instruments (°C);
- α = the area coefficient of thermal expansion of the piston-cylinder assembly, taken to be 21.6×10^{-6} K^{-1};
- t_c = the corrected measured temperature of the cylinder holder (°C);
- P_r = the value of the residual pressure in the bell-jar (Pa) (absolute mode only).

From each value of P_c, the pilot laboratory calculated the mean effective area of the piston-cylinder, from given values of ring-weight mass, using the equation:

$$A_p = \left(\frac{9.806\,65 \times \Sigma M}{P_\mathrm{c}} \right),$$

where

- A_p = mean effective area at pressure P_c and at a temperature of 20 °C (m^2);
- ΣM = the total mass of the piston unit and supported ring weights, corrected for buoyancy (kg).

The standard error, defined as the standard deviation in each participant's value for effective area divided by the square root of the number of measurements taken, was also calculated.

6. Results

Data from each participant are given in the tables and a graphic analysis is given in the figures.

Figure 1 shows the difference between each participant's mean values of effective area and the unweighted mean values of all data at each pressure, absolute mode (i.e. participant's value minus the mean value).

After taking part in the exercise, the CSMU and the CSIRO reported problems with their standards [17, 18]. Thus Figure 2 shows the difference between each participant's mean values of effective area and a revised unweighted mean value of all data at each pressure, excluding the CSMU and CSIRO data.

Figure 4 and Figure 8 suggest that somewhere between NPL3 and NPL4 the effective area of the

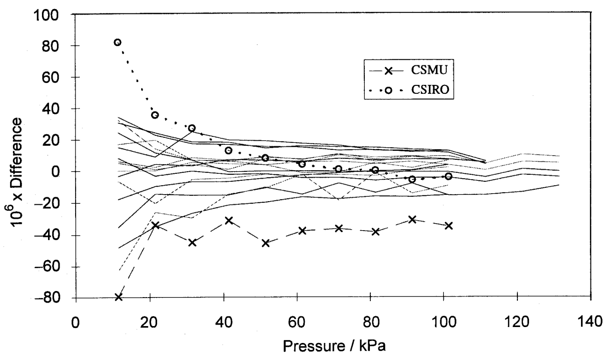

Figure 1. Difference between each participant's mean values of effective area and the mean values of all data, absolute mode.

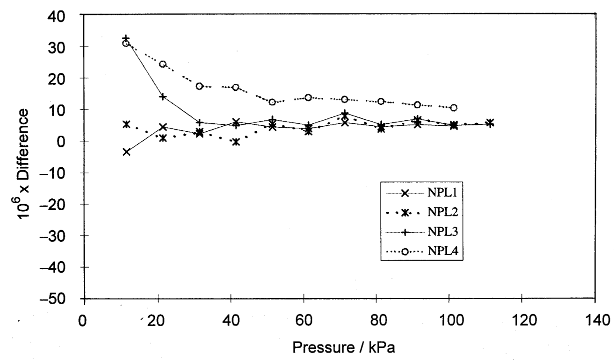

Figure 4. Difference between each of the NPL mean values of effective area and the reference values of Figure 3, absolute mode.

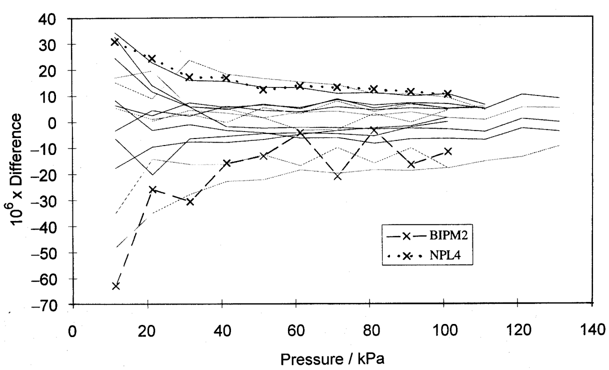

Figure 2. Difference between each participant's mean values of effective area and the mean values excluding CSMU and CSIRO data, absolute mode.

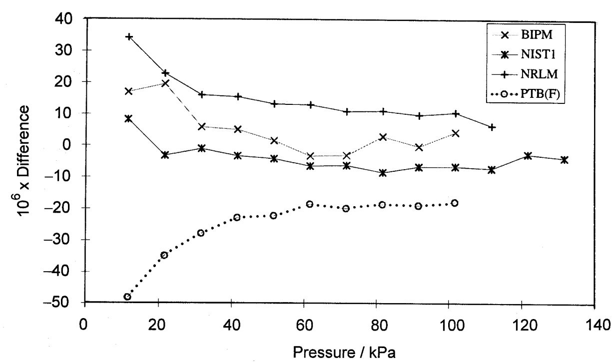

Figure 5. Difference between the BIPM, NIST1, NRLM and PTB(F) mean values of effective area and the reference values of Figure 3, absolute mode.

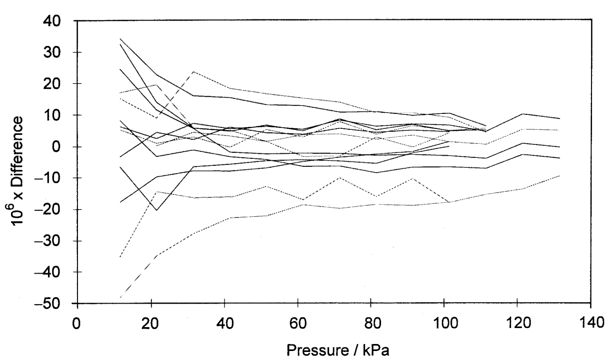

Figure 3. Difference between each participant's mean values of effective area and the unweighted mean of all data at each pressure, excluding CSMU, CSIRO, BIPM2 and NPL4 data, absolute mode.

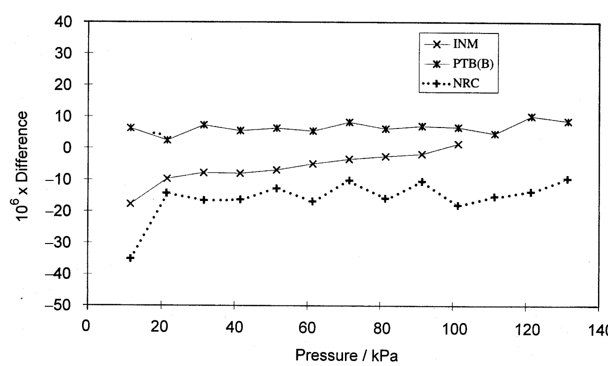

Figure 6. Difference between the INM, PTB(B) and NRC mean values of effective area and the reference values of Figure 3, absolute mode.

transfer standard changed significantly and the BIPM reported problems in taking measurement set BIPM2. Figure 3 therefore shows the difference between each participant's mean values of effective area and a further revised unweighted mean value of all data at each pressure, excluding the CSMU, CSIRO, BIPM2 and NPL4 data. This "datum" value was the reference used in Figures 4 to 7. Figure 4 groups data from NPL1, NPL2, NPL3 and NPL4. Figures 5 to 7 show the remaining participants' data grouped for clarity of presentation. To aid clarity, no error bars are shown in these figures.

Figures 8 and 9 show results from all four NPL calibrations at pressures of 101 kPa and 31 kPa, respectively, absolute mode. For each calibration, three error bars are shown. The first shows the calculated standard error in the measurements, the second the claimed uncertainty of the standard due to systematic

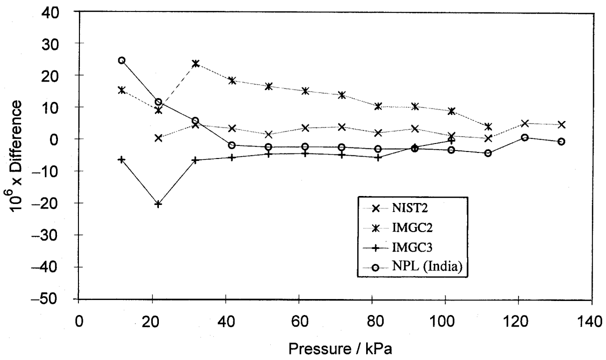

Figure 7. Difference between the NIST2, IMGC2, IMGC3 and NPL (India) mean values of effective area and the reference values of Figure 3, absolute mode.

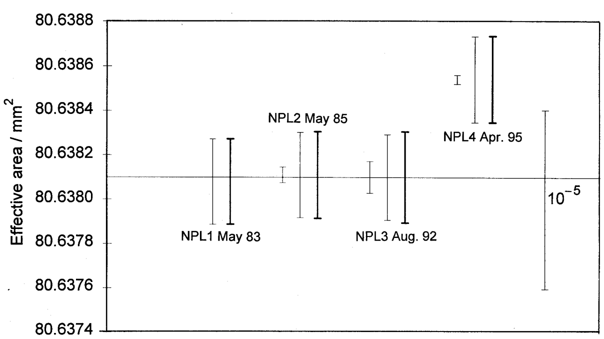

Figure 8. Successive NPL calibrations at 101 kPa, absolute mode (horizontal line is mean of NPL1, NPL2 and NPL3 values at this pressure).

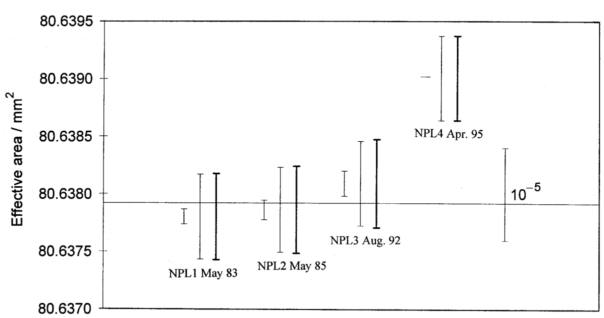

Figure 9. Successive NPL calibrations at 31 kPa, absolute mode (horizontal line is mean of NPL1, NPL2 and NPL3 values at this pressure).

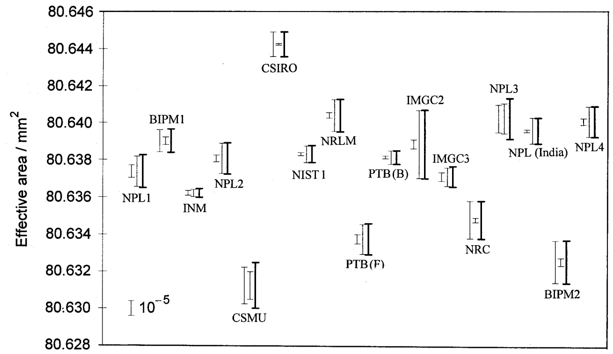

Figure 10. All results at 11 kPa, absolute mode.

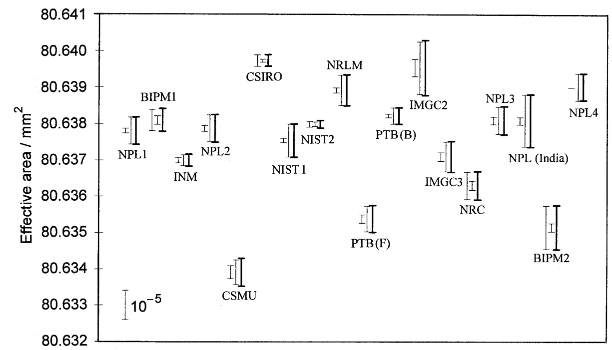

Figure 11. All results at 31 kPa, absolute mode.

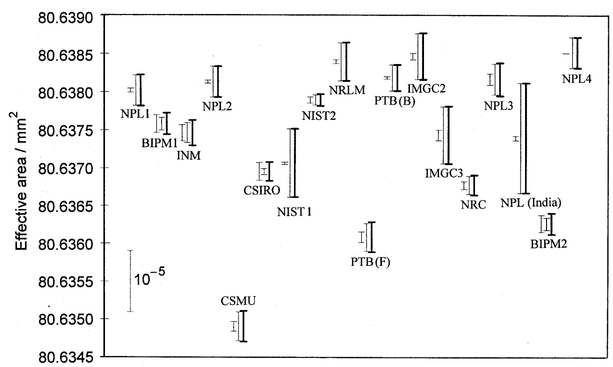

Figure 12. All results at 91 kPa, absolute mode.

effects, and the third the result of adding the two by the root-sum-of-squares method. The horizontal lines in Figures 8 and 9 show the mean effective area from the first three NPL calibrations at 101 kPa and 31 kPa, respectively. Figures 10 to 13 show the full calibration results obtained by each of the participants as calculated effective area at pressures of 11 kPa, 31 kPa, 91 kPa and 101 kPa, in the absolute mode, in order of participation. As before, for each participant at each pressure, three error bars are shown. The first shows the calculated standard error in their measurements, the second the claimed uncertainty of their standard due to systematic effects, and the third the result of adding the two by the root-sum-of-squares method. All uncertainties are at a coverage factor $k = 1$.

Summary graphs for the gauge mode are shown in Figures 14 and 15, showing the differences between each participant's mean effective areas and the unweighted mean value of all data at each pressure, with participants grouped for clarity. Again, for clarity, no error bars are shown in these figures. Figures 16 to 19 show the full calibration results obtained by each of the participants as calculated effective area at pressures of 11 kPa, 31 kPa, 91 kPa and 101 kPa, in the gauge mode, in order of participation, with the error bars as before.

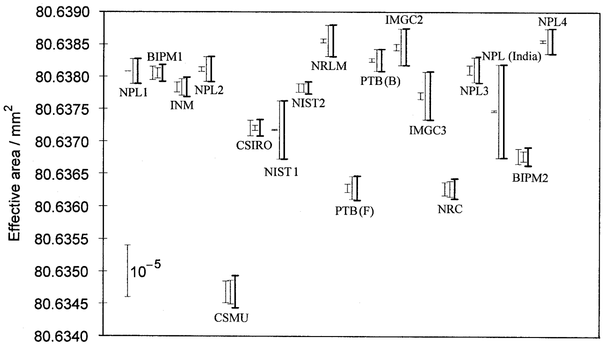

Figure 13. All results at 101 kPa, absolute mode.

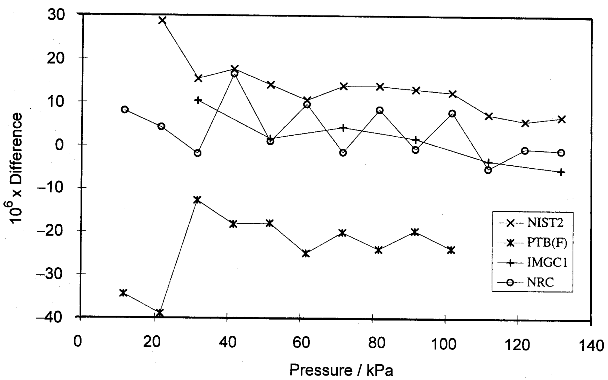

Figure 14. Difference between the NIST2, PTB(F), IMGC1 and NRC mean values of effective area and the mean values of all data, gauge mode.

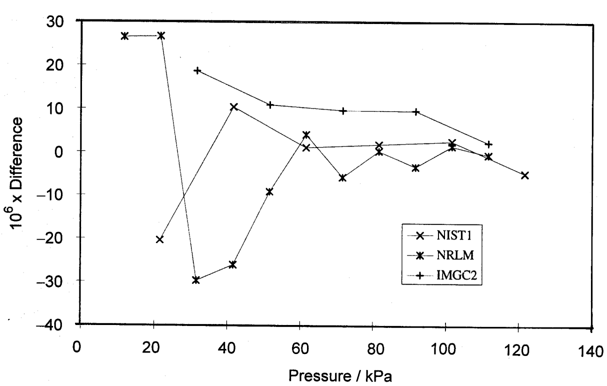

Figure 15. Difference between the NIST1, NRLM and IMGC2 mean values of effective area and the mean values of all data, gauge mode.

Tables 1 to 4 show the mean effective area values and calculated standard error for each participant in both the absolute and gauge modes. Each participant's claimed uncertainties are given in Tables 5 and 6. A timetable of the measurements is given in Table 7.

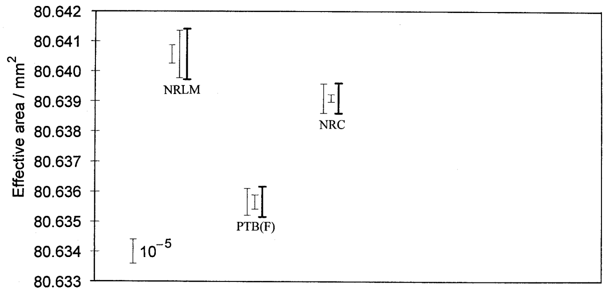

Figure 16. All results at 11 kPa, gauge mode.

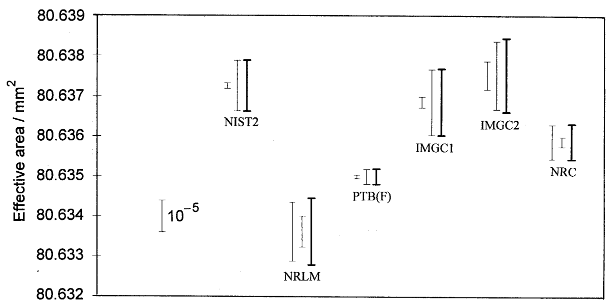

Figure 17. All results at 31 kPa, gauge mode.

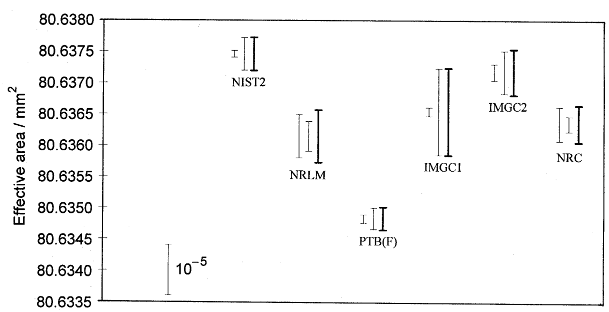

Figure 18. All results at 91 kPa, gauge mode.

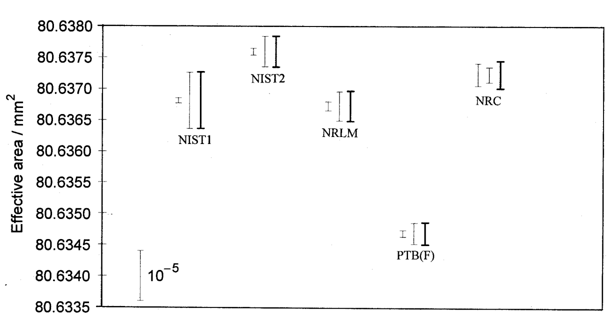

Figure 19. All results at 101 kPa, gauge mode.

Table 1. Mean calculated effective area for each participant at each nominal pressure, absolute mode/mm^2.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NPL1	80.637 37	80.638 32	80.637 80	80.638 24	80.637 98	80.638 02	80.638 03	80.638 08	80.638 02	80.638 08	–	–	–
BIPM1	80.639 01	80.639 54	80.638 09	80.638 16	80.637 75	80.637 44	80.637 32	80.637 96	80.637 58	80.638 05	–	–	–
INM	80.636 21	80.637 18	80.636 99	80.637 11	80.637 07	80.637 31	80.637 29	80.637 52	80.637 46	80.637 83	–	–	–
NPL2	80.638 07	80.638 04	80.637 86	80.637 73	80.638 06	80.637 95	80.638 20	80.638 03	80.638 13	80.638 11	80.638 24	–	–
CSMU	80.631 24	80.635 23	80.633 90	80.635 13	80.633 76	80.634 48	80.634 45	80.634 41	80.634 90	80.634 67	–	–	–
CSIRO	80.644 25	80.640 82	80.639 72	80.638 69	80.638 09	80.637 87	80.637 47	80.637 56	80.636 95	80.637 20	–	–	–
NIST1	80.638 31	80.637 70	80.637 53	80.637 48	80.637 29	80.637 19	80.637 06	80.637 04	80.637 06	80.637 17	80.637 20	80.637 17	80.637 14
NIST2	–	80.637 98	80.637 98	80.638 02	80.637 75	80.638 00	80.637 89	80.637 90	80.637 89	80.637 82	80.637 83	80.637 82	80.637 86
NRLM	80.640 41	80.639 80	80.638 91	80.639 00	80.638 69	80.638 75	80.638 44	80.638 61	80.638 39	80.638 55	80.638 29	–	–
PTB(F)	80.633 76	80.635 15	80.635 38	80.635 91	80.635 84	80.636 21	80.635 97	80.636 23	80.636 08	80.636 27	–	–	–
PTB(B)	80.638 15	80.638 16	80.638 21	80.638 20	80.638 14	80.638 15	80.638 24	80.638 23	80.638 18	80.638 25	80.638 16	80.638 21	80.638 16
IMGC2	80.638 87	80.638 68	80.639 53	80.639 23	80.638 97	80.638 94	80.638 70	80.638 58	80.638 46	80.638 45	80.638 13	–	–
IMGC3	80.637 12	80.636 32	80.637 09	80.637 29	80.637 26	80.637 36	80.637 19	80.637 28	80.637 43	80.637 70	–	–	–
NRC	80.634 81	80.636 80	80.636 30	80.636 43	80.636 60	80.636 34	80.636 76	80.636 43	80.636 77	80.636 26	80.636 54	80.636 28	80.636 68
NPL3	80.640 27	80.639 09	80.638 09	80.638 14	80.638 17	80.638 11	80.638 27	80.638 14	80.638 16	80.638 10	80.638 20	–	–
NPL (India)	80.639 62	80.638 89	80.638 08	80.637 60	80.637 43	80.637 53	80.637 38	80.637 49	80.637 39	80.637 46	80.637 46	80.637 46	80.637 43
BIPM2	80.632 57	80.635 87	80.635 15	80.636 47	80.636 56	80.637 36	80.635 88	80.637 44	80.636 26	80.636 76	–	–	–
NPL4	80.640 13	80.639 92	80.639 01	80.639 11	80.638 61	80.638 81	80.638 62	80.638 72	80.638 51	80.638 54	–	–	–

Table 2. Standard error of each participant's mean calculated effective area at each nominal pressure, absolute mode/mm^2.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NPL1	0.000 34	0.000 15	0.000 07	0.000 14	0.000 00	0.000 09	0.000 06	0.000 04	0.000 03	0.000 00	–	–	–
BIPM1	0.000 59	0.000 33	0.000 29	0.000 12	0.000 11	0.000 06	0.000 06	0.000 06	0.000 12	0.000 11	–	–	–
INM	0.000 13	0.000 10	0.000 07	0.000 03	0.000 04	0.000 02	0.000 06	0.000 03	0.000 11	0.000 08	–	–	–
NPL2	0.000 18	0.000 16	0.000 08	0.000 05	0.000 05	0.000 04	0.000 02	0.000 04	0.000 02	0.000 04	0.000 05	–	–
CSMU	0.000 99	0.000 80	0.000 18	0.000 41	0.000 19	0.000 30	0.000 06	0.000 19	0.000 06	0.000 17	–	–	–
CSIRO	0.000 67	0.000 19	0.000 16	0.000 09	0.000 16	0.000 09	0.000 07	0.000 07	0.000 12	0.000 12	–	–	–
NIST1	0.000 08	0.000 06	0.000 06	0.000 04	0.000 04	0.000 02	0.000 04	0.000 03	0.000 01	0.000 01	0.000 01	0.000 04	0.000 06
NIST2	–	0.000 12	0.000 08	0.000 12	0.000 11	0.000 08	0.000 05	0.000 07	0.000 04	0.000 07	0.000 03	0.000 01	0.000 02
NRLM	0.000 15	0.000 23	0.000 07	0.000 10	0.000 08	0.000 04	0.000 06	0.000 06	0.000 02	0.000 03	0.000 04	–	–
PTB(F)	0.000 25	0.000 20	0.000 12	0.000 12	0.000 08	0.000 08	0.000 08	0.000 08	0.000 07	0.000 06	–	–	–
PTB(B)	0.000 07	0.000 04	0.000 05	0.000 04	0.000 02	0.000 02	0.000 04	0.000 02	0.000 01	0.000 03	0.000 01	0.000 01	0.000 00
IMGC2	0.000 25	0.000 12	0.000 24	0.000 13	0.000 12	0.000 10	0.000 07	0.000 05	0.000 04	0.000 05	0.000 05	–	–
IMGC3	0.000 23	0.000 19	0.000 12	0.000 16	0.000 06	0.000 11	0.000 07	0.000 07	0.000 07	0.000 05	–	–	–
NRC	0.001 00	0.000 12	0.000 38	0.000 12	0.000 22	0.000 09	0.000 16	0.000 12	0.000 05	0.000 10	0.000 10	0.000 07	0.000 10
NPL3	0.000 74	0.000 32	0.000 11	0.000 18	0.000 06	0.000 10	0.000 05	0.000 07	0.000 07	0.000 07	0.000 07	–	–
NPL (India)	0.000 07	0.000 06	0.000 10	0.000 06	0.000 08	0.000 06	0.000 03	0.000 03	0.000 03	0.000 01	0.000 02	0.000 03	0.000 06
BIPM2	0.001 14	0.001 14	0.000 60	0.000 51	0.000 74	0.000 45	0.000 18	0.000 42	0.000 11	0.000 12	–	–	–
NPL4	0.000 18	0.000 11	0.000 00	0.000 06	0.000 00	0.000 06	0.000 00	0.000 03	0.000 00	0.000 02	–	–	–

Table 3. Mean calculated effective area for each participant at each nominal pressure, gauge mode/mm^2.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NIST1	–	80.636 80	–	80.637 23	–	80.637 06	–	80.636 86	–	80.636 81	–	80.636 79	–
NIST2	–	80.640 77	80.637 25	80.637 82	80.637 57	80.637 82	80.637 53	80.637 83	80.637 46	80.637 59	80.637 40	80.637 64	80.637 20
NRLM	80.640 56	80.640 59	80.633 61	80.634 29	80.635 70	80.637 30	80.635 95	80.636 74	80.636 14	80.636 72	80.636 77	–	–
PTB(F)	80.635 65	80.635 30	80.634 99	80.634 93	80.634 99	80.634 96	80.634 79	80.634 78	80.634 82	80.634 68	–	–	–
IMGC1	–	–	80.636 84	–	80.636 57	–	80.636 76	–	80.636 54	–	80.636 54	–	80.636 22
IMGC2	–	–	80.637 51	–	80.637 32	–	80.637 19	–	80.637 18	–	80.637 00	–	–
NRC	80.639 08	80.638 79	80.635 86	80.637 73	80.636 52	80.637 74	80.636 29	80.637 39	80.636 35	80.637 23	80.636 40	80.637 13	80.636 58

Table 4. Standard error of each participant's mean calculated effective area at each nominal pressure, gauge mode/mm^2.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NIST1	–	0.000 04	–	0.000 02	–	0.000 07	–	0.000 10	–	0.000 04	–	0.000 03	–
NIST2	–	0.000 15	0.000 07	0.000 06	0.000 05	0.000 02	0.000 03	0.000 03	0.000 06	0.000 05	0.000 04	0.000 02	0.000 06
NRLM	0.000 30	0.000 28	0.000 74	0.000 67	0.000 29	0.000 26	0.000 36	0.000 15	0.000 35	0.000 07	0.000 15	–	–
PTB(F)	0.000 45	0.000 17	0.000 05	0.000 13	0.000 13	0.000 13	0.000 09	0.000 05	0.000 07	0.000 05	–	–	–
IMGC1	–	–	0.000 13	–	0.000 05	–	0.000 03	–	0.000 07	–	0.000 06	–	0.000 05
IMGC2	–	–	0.000 35	–	0.000 19	–	0.000 18	–	0.000 13	–	0.000 12	–	–
NRC	0.000 49	0.000 20	0.000 42	0.000 13	0.000 24	0.000 19	0.000 31	0.000 21	0.000 27	0.000 18	0.000 19	0.000 20	0.000 12

Table 5. Each participant's claimed uncertainty due to systematic effects (k = 1) at each nominal pressure, absolute mode/Pa.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NPL1	0.115	0.129	0.143	0.157	0.171	0.185	0.199	0.213	0.227	0.241	–	–	–
BIPM1	0.029	0.037	0.045	0.053	0.061	0.069	0.077	0.085	0.093	0.101	–	–	–
INM	0.027	0.042	0.057	0.072	0.087	0.102	0.117	0.132	0.147	0.162	–	–	–
NPL2	0.115	0.129	0.143	0.157	0.171	0.185	0.199	0.213	0.227	0.241	0.255	–	–
CSMU	0.105	0.119	0.133	0.147	0.161	0.175	0.189	0.203	0.217	0.231	–	–	–
CSIRO	0.007	0.012	0.017	0.022	0.027	0.032	0.037	0.042	0.047	0.052	–	–	–
NIST1	0.062	0.118	0.174	0.230	0.286	0.342	0.398	0.454	0.510	0.566	0.622	0.678	0.734
NIST2	–	0.017	0.025	0.033	0.041	0.049	0.057	0.065	0.073	0.081	0.089	0.097	0.105
NRLM	0.122	0.142	0.162	0.182	0.202	0.222	0.242	0.262	0.282	0.302	0.322	–	–
PTB(F)	0.113	0.125	0.137	0.149	0.161	0.173	0.185	0.197	0.209	0.221	–	–	–
PTB(B)	0.050	0.068	0.086	0.104	0.122	0.140	0.158	0.176	0.194	0.212	0.230	0.248	0.265
IMGC2	0.261	0.271	0.281	0.291	0.301	0.311	0.321	0.331	0.341	0.351	0.361	–	–
IMGC3	0.068	0.112	0.156	0.200	0.244	0.288	0.332	0.376	0.420	0.464	–	–	–
NRC	0.017	0.032	0.047	0.062	0.077	0.092	0.107	0.122	0.137	0.152	0.167	0.182	0.197
NPL3	0.115	0.129	0.143	0.157	0.171	0.185	0.199	0.213	0.227	0.241	0.255	–	–
NPL (India)	0.100	0.190	0.280	0.370	0.460	0.550	0.640	0.730	0.820	0.910	1.000	1.090	1.180
BIPM2	0.029	0.037	0.045	0.053	0.061	0.069	0.077	0.085	0.093	0.101	–	–	–
NPL4	0.115	0.129	0.143	0.157	0.171	0.185	0.199	0.213	0.227	0.241	–	–	–

Table 6. Each participant's claimed uncertainty due to systematic effects (k = 1) at each nominal pressure, gauge mode/Pa.

Participant	11 kPa	21 kPa	31 kPa	41 kPa	51 kPa	61 kPa	71 kPa	81 kPa	91 kPa	101 kPa	111 kPa	121 kPa	131 kPa
NIST1	–	0.118	–	0.230	–	0.342	–	0.454	–	0.566	–	0.678	–
NIST2	–	0.237	0.245	0.253	0.261	0.269	0.277	0.285	0.293	0.301	0.309	0.317	0.325
NRLM	0.112	0.132	0.152	0.172	0.192	0.212	0.232	0.252	0.272	0.292	0.312	–	–
PTB(F)	0.032	0.052	0.072	0.092	0.112	0.132	0.152	0.172	0.192	0.212	–	–	–
IMGC1	–	–	0.315	–	0.473	–	0.631	–	0.789	–	0.947	–	1.105
IMGC2	–	—	0.331	–	0.351	–	0.371	–	0.391	–	0.411	–	–
NRC	0.016	0.032	0.046	0.062	0.076	0.092	0.106	0.122	0.136	0.152	0.166	0.182	0.196

Table 7. Month and year of each participant's measurements.

NPL1	May 1983
BIPM1	November 1984
INM	December 1984
NPL2	May 1985
CSMU	March 1987
CSIRO	Aug.-Sept. 1987
NIST1	Dec. 1987-Feb. 1988
NIST2	April 1988
NRLM	August 1990
PTB(F)	Nov.-Dec. 1990
PTB(B)	January 1991
IMGC1	June-July 1991
IMGC2	July-Aug. 1991
IMGC3	Oct.-Nov. 1991
NRC	March 1992
NPL3	August 1992
NPL (India)	January 1994
BIPM2	June 1994
NPL4	April 1995

7. Discussion

From the absolute mode figures it may be seen that the maximum difference between any two laboratories was approximately 1.6×10^{-5} ppm at the lowest pressure of 11 kPa. At the highest pressure where measurements were taken by all laboratories, 101 kPa, the maximum difference was approximately 4.5×10^{-5} ppm. When the results from those laboratories subsequently reporting errors with their standards and other problems (CSMU, CSIRO, BIPM2 and NPL4) are disregarded, the maximum difference falls to approximately 8.3×10^{-5} ppm at 11 kPa and 3.0×10^{-5} ppm at 101 kPa. The differences are clearly greater than would be expected from the claimed uncertainties of the participants.

Disagreements were also found in measurements made in the gauge mode with a difference between laboratories of 7.0×10^{-5} ppm at 21 kPa and 3.5×10^{-5} ppm at 101 kPa.

Possible causes of error in the comparison include both the measurement of temperature and, in the absolute mode, residual pressure. The temperature coefficient of the piston-cylinder was taken to be the traditional value of 2.16×10^{-5} ppm K^{-1}. NIST1 reported [21] some additional data which suggested that the value was 2.09×10^{-5} ppm K^{-1}, that is, different by 0.7×10^{-6} ppm K^{-1}. The NIST also reported a shift in the thermometer's calibration corrections of approximately 0.1 K, corresponding to about 2×10^{-6} ppm in effective area.

Errors ascribed to the performance of the Pirani gauge could have been marginally larger but the magnitude of these errors is not sufficient to explain fully the differences between the participants.

The results also show that there was no consistent variation of effective area with applied pressure, although there is evidence of a difference between the results obtained in the absolute mode and those obtained in the gauge mode. Such differences have been seen in other data [19, 20], although in some cases they may be a result of aerodynamic effects upon the spinning weights [20]. Indeed, one of the participants, NIST1, investigated the aerodynamic effect using the transfer standard and reported [21] their gauge mode results corrected to a zero rotational speed. This was not done by other participants. Analysis of the gauge-mode results is further complicated by the fact that participants carried out their measurements at different line pressures and the information reported did not always allow an accurate calculation of buoyancy effects: in some cases it was necessary to assume a gas density of 1.2 kg m^{-3} in the bell-jar. Also, some participants who did take measurements in the gauge mode did so only at certain nominal pressures, which were not the same for each participant.

8. Subsequent modifications to participants' standards

As the comparison took place over a long period of time, some participants modified their standards after taking the measurements reported in this paper. A brief description of the modifications is therefore given.

8.1 National Physical Laboratory (UK)

Between the results presented in this report as NPL2 and NPL3, the optical system of the barometer, including the laser and interferometers, was replaced. Following the measurements giving rise to NPL3, the U-tube was dismantled to allow the repair of a valve.

8.2 Bureau International des Poids et Mesures

In 1993 the manometer was completely renovated: this included the vacuum system, pipework and control system for the measurements. The mercury was purified and distilled and the measurement chambers, auxiliary manometer and electromagnetic valves were cleaned. Also, the optical system was cleaned and realigned.

8.3 Institut National de Métrologie

The laser interferometer system has been replaced and the flexible tube between the two cells, which was made of polypropylene, has been replaced by one made of Teflon PFA. In addition, the vacuum pumping system has been modified.

8.4 Slovak Institute of Metrology

Within the period 1990-1993 the manometer was completely disassembled and reassembled in a new laboratory. The manometer is now equipped with an anti-vibration base and is in a laboratory with substantially better air conditioning. Some minor modifications, including the addition of a new computer-controlled interferometer, were also made at this time.

8.5 Commonwealth Scientific and Industrial Research Organization

Following the comparison, a leak was discovered in the reference vacuum. Although experiments were undertaken with different types of float, the original is still in use.

8.6 National Institute of Standards and Technology

NIST1: since the comparison, the mercury in the manometer has been replaced by mercury of measured density and a correction is now applied for the effects of diffraction on the propagation of the ultrasound.
NIST 2: none.

8.7 National Research Laboratory of Metrology

Since the comparison, the seals on the moving chambers have been changed from rubber to stainless-steel bellows, the U-tube columns have been increased in diameter from 49.5 mm to 73.9 mm, and the mercury diffusion pump has been replaced by a turbo-molecular pump with a liquid-nitrogen cold trap [22].

8.8 Physikalisch-Technische Bundesanstalt (F)

Following the comparison, the instrument was dismantled and sent to another institute for reassembly.

8.9 Physikalisch-Technische Bundesanstalt (B)

It was discovered that, due to its positioning, the capacitance manometer was not giving an accurate measurement of the residual pressure. The pressure at the mercury surface should instead be calculated from the mercury-vapour pressure at the cistern temperature. If applied retrospectively to the results given in this paper, the effective areas calculated for PTB(B) would need to be multiplied by the factor $(1 + \Delta p/p)$ with Δp equal to 0.09 Pa.

8.10 Istituto di Metrologia "G. Colonnetti"

IMGC1 has not been modified but its uncertainty has been re-evaluated and its effective area recalculated from new dimensional measurement.
IMGC2: since the comparison, the manometer's interferometer has been modified which has resulted in the ability to use smaller retroreflectors and therefore smaller floats. In addition, a new interferometric manometer making use of larger-diameter columns and using a capacitance manometer rather than a Pirani gauge has been built and put into operation.
IMGC3: a revised system for data acquisition has been introduced and a reduction in the estimated uncertainty has been achieved.

8.11 National Research Council (Canada)

Since the comparison, a new Schwien manometer with advanced electronics and microprocessor controls has been obtained and used as a reference pressure standard at the NRC.

8.12 National Physical Laboratory (India)

None.

9. Conclusion

The results have allowed some participants to identify and to rectify problems associated with their standards. Even so, the remaining results confirm the conclusions of the interim report – that there were systematic differences between participants which were well in excess of the repeatability of the transfer standard and the uncertainties generally attributed to the participants' standards.

Such a conclusion is less than satisfactory and the exercise, which relates to an important pressure range, will be repeated in an attempt to identify the sources of the discrepancies.

The new comparison will again be undertaken in both gauge and absolute modes, and will be conducted more quickly than the exercise reported here. Procedures for both the practical comparison and the calibration of ancillary equipment will be more clearly defined and more rigidly adhered to.

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