A Bi-Lateral Comparison of a 0.5 gram to 0.001 gram Weight Set

N M Raymond
Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom
TW11 0LW

Dr L Nielsen
Danish Institute of Fundamental Metrology
Building 307
Anker Engelunds Vej 1
DK - 2800 Lyngby
Denmark

ABSTRACT

A bi-lateral comparison of a 0.5 gram to 0.001 gram set of weights has been carried out between the National Physical Laboratory (NPL) and the Danish Institute of Fundamental Metrology (DFM). The mass values of sixteen out of seventeen measured weights agree to within the combined standard uncertainty (k=1) of the two laboratories. This represents an excellent agreement and gives confidence in the measurements performed by both laboratories.

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

Approved on behalf of the Managing Director, NPL,
by Dr G Torr, Head of Centre,
Centre for Mechanical and Acoustical Metrology

1 INTRODUCTION

A bi-lateral comparison of a 0.5 gram to 0.001 gram set of weights was carried out between the National Physical Laboratory (NPL), United Kingdom and the Danish Institute of Fundamental Metrology (DFM), Denmark. This is the first comparison made at this level by either laboratory and both were keen to ensure that agreement between their measurements was within their estimated uncertainties for the weights. It was agreed that NPL would provide a set of weights for the comparison.

The set of weights used for this comparison was supplied by Precisa Balances Limited. This set is identified as NPLW65 parts 'C' and 'D' and is housed in a wooden box which contains two plastic lined compartments, labelled 'C' and 'D'. Part 'C' of the set comprises of non-magnetic stainless steel polygonal wire weights of nominal mass 0.5 gram to 0.001 gram shaped according to the OIML recommendation [1]. Part 'D' of the set is similar to part 'C' except the shape of each weight is slightly altered to distinguish them from the part 'C' weights. All of the weights have an assumed density of 8 050 kg m^{-3} based on the measured density of larger weights from the same manufacturer. The set was purchased from Precisa in 1994 and has been weighed at NPL in February 1994 and March 1995. The weights have not been used for any other purpose.

The weights were calibrated at NPL during the period 24 to 29 January 1996. They were then taken by air to the EUROMET Mass Contact Persons meeting in Madrid on 5 February 1996 and handed to the DFM representative. The weights remained in Madrid for five days before being taken to Denmark and were calibrated by DFM during the period 16 to 30 April 1996. The weights were returned to NPL on 20 May 1996 and calibrated again during the period 13 to 21 June 1996. A further calibration of part 'C' of the set without part 'D' was carried out at NPL during the period 9 to 22 August 1996.

2 EQUIPMENT USED FOR COMPARISON

2.1 STANDARDS AND TRACEABILITY

2.1.1 NPL

Three standards of nominal mass 1 gram were used to calibrate set NPLW65. Two of the 1 gram standards are cylindrical stainless steel weights of stainless steel with a volume of 0.127 6 cm^3 and a standard uncertainty of $\pm$ 0.000 5 cm^3. These weights are taken from a 500 grams to 1 gram set known as NPLW43, which has an assumed density of 7 840 kg m^{-3} based on the measurement of the density of larger weights from the same manufacturer. The third 1 gram standard is a cylindrical weight of platinum-iridium with a volume of 0.046 9 cm^3 and a standard uncertainty of 0.000 005 cm^3. This weight is taken from a 500 grams to 1 milligram set known as PI Grams, which has an assumed density of 21 343 kg m^{-3} based on measurements made by the Board of Trade [2]. The three standards are traceable by sub-division to the International Prototype Kilogram held at the International Bureau of Weights and Measures (BIPM), through the UK National Prototype Kilogram No 18 (Kg 18) which was last calibrated by BIPM in 1991. Figure 1 shows the traceability of PI Grams and NPLW 43 back to Kg 18.

2.1.2 DFM

The 1g weight W1g in the weight set DFM 431 was used as reference standard for the calibration. This weight is made of stainless steel and has a volume of 0.125 90 cm^3 measured with a standard uncertainty of ± 0.000 25 cm^3 by hydrostatic weighing. The mass of W1g has been measured by subdivision from the 1kg weight W1kg in the weight set DFM 432. The weight W1kg has been calibrated directly against the Danish National Prototype Kilogram K48, which is traceable to the International Prototype Kilogram through periodic calibrations at BIPM; K48 was last calibrated at BIPM in June 1990.

2.2 BALANCES

2.2.1 NPL

Two balances were used for this comparison. A Sartorius S4 single-pan balance was used to calibrate the weights before they were sent to DFM. This balance had a capacity of 4 grams with a readability of 0.1 µg and a standard deviation of 0.2 µg on the repeatability of twenty consecutive readings, the balance being arrested between each reading. When the weights were returned from DFM they were calibrated using a Mettler ME22 single-pan balance. This balance has a capacity of 3 grams with a readability of 0.1 µg and a standard deviation of 0.3 µg on the repeatability of twenty consecutive readings. The August 1996 calibration of part 'C' of the set was carried out using the Sartorius S4 balance, which in June 1996 had been modified by Sartorius to have a capacity of 5 grams. The balance is now known as the Sartorius C5S. It has the same readability of 0.1 µg and following re-assessment shows a standard deviation of 0.3 µg on the repeatability of twenty consecutive readings.

2.2.2 DFM

The calibration of the masses were performed on a Mettler UM3 single pan mass comparator. This comparator has a capacity of 3 g and a resolution of 0.1 µg. The standard deviation of the mass difference of two weights *A* and *B* measured using the *ABBA* weighing scheme is typically 0.5 µg.

2.3 AIR DENSITY MEASUREMENTS

When weights of different volume were being compared a correction was made for the air buoyancy which necessitated knowing the air density at the time of the weighing. The air density was calculated from the four parameters, air pressure, temperature, humidity dew point and carbon dioxide concentration, using the empirical equation recommended by CIPM [3]. Sections 2.3.1 and 2.3.2 describe the equipment used for the measurement of each parameter and the associated standard uncertainty. Table 1 gives the ranges of the measured atmospheric conditions for each calibration made at NPL and DFM.

2.3.1 NPL Measurements

2.3.1a Air Pressure

The air pressure was measured using a Druck DPI 140 vibrating cell barometer whose uncertainty, incorporating an element for drift between calibrations, is ± 0.05 mbar at a coverage factor of k=1. This corresponds to a standard uncertainty of ± 0.000 06 kg m^{-3} in air density.

2.3.1b Temperature

The temperature was measured using an Edale thermistor which has a calibration uncertainty of ± 0.03 °C at a coverage factor of k=1. When combined with the uncertainty of the temperature gradient across the balance and the drift of the instrument between calibrations, the uncertainty becomes ± 0.2 °C which corresponds to a standard uncertainty of ± 0.000 90 kg m^{-3} in the air density.

2.3.1c Humidity dew point

The humidity dew point was measured using a Michell series 3000 cooled mirror hygrometer. This has an uncertainty of ± 0.11 °C at a coverage factor of k=1. This combined with the uncertainty due to the dew point gradient across the laboratory and an element for the drift between calibrations gives a total uncertainty of ± 0.25 °C which corresponds to a standard uncertainty of ± 0.000 07 kg m^{-3} in the air density.

2.3.1d Carbon dioxide concentration

This has not been measured during this comparison but was assumed to be 400 ppm with an uncertainty of ± 50 ppm. This gives a standard uncertainty in the air density of ± 0.000 03 kg m^{-3}.

2.3.2 DFM Measurements

2.3.2a Air Pressure

The air pressure was measured using a Digiquartz Digital Barometer, model 740-16B from Paroscientific Inc. The standard uncertainty of the pressure measured with this instrument has been estimated to ± 5 Pa, corresponding to a standard uncertainty of ± 0.000 05 kg m^{-3} in the calculated air density.

2.3.2b Temperature

The temperature was measured with Pt100 resistance thermometer; its resistance is measured with a Kelvimat Transmitter 4302 made by Burster. The resistance thermometer and the transmitter are calibrated as separate units. The measured resistance is converted to temperature using a second order calibration curve fitted to the calibration data obtained for the Pt100 element. The standard uncertainty of the measured temperature has been estimated to ± 6 mK, corresponding to a standard uncertainty of ± 0.000 03 kg m^{-3} in the calculated air density.

2.3.2c Humidity dew point

The humidity dew point of the ambient air was measured using a Michell series 4000 cooled mirror hygrometer. The standard uncertainty of the measured dew point has been estimated to ± 0.1 K corresponding to a standard uncertainty of ± 0.000 04 kg m^{-3} in the calculated air density.

2.3.2d Carbon dioxide concentration

The carbon dioxide content of the ambient air was measured using a Brüel & Kjær photo-acoustical Multi Gas-monitor, type 1302. The standard uncertainty of the measured carbon dioxide content has been estimated to ± 20 ppm corresponding to a standard uncertainty of ± 0.000 01 kg m^{-3} in the calculated air density.

3 WEIGHING SCHEME

3.1 NPL MEASUREMENTS

The set was calibrated by NPL employing a sub-division method [4] and weighing in a double substitution mode. Corrections for air buoyancy were made using the CIPM formula. No corrections were made for the difference in the height of centre of gravity as this is negligible. The mass values of the weights were calculated from the mass differences obtained during the calibration using a least squares method [5].

Part 'C' of the set was calibrated without part 'D' in August 1996. To allow sub-division, additional weights of known mass were calibrated as part of the set. These weights are listed in Table 6 along with the mass values obtained for these weights in this calibration and known values from when the all the weights in the set were calibrated in July 1996.

3.2 DFM MEASUREMENTS

The calibration was by subdividing the mass of the reference standard W1g according to DFM's internal method [6]. Two subdivisions were carried out independently. One on part C and one on part D of the set. In order to create two sets suitable for subdivision, the weights listed in Table 7 were added to both sets.

The mass differences between selected weight combinations *A* and *B* were measured by weighing according to Borda's substitution principle. One difference was based on four readings taken in the sequence *ABBA*, and this sequence was repeated 5 times. Each mass difference observed was corrected for air buoyancy and differences in the vertical position of the centres of gravity of the weights. The air buoyancy corrections were calculated from the volumes or densities known *a priori* and air densities calculated from continuous measurements of pressure, temperature, humidity and CO_2 content using the CIPM formula. From the observed, corrected mass differences the unknown masses have been calculated for each decade by the method of least squares using the mass of W1g as a restraint.

The mass corrections obtained for the additional weights used in each of the two sub-divisions are given in Table 7 together with the average of their known values obtained since 1992.

4 UNCERTAINTIES

4.1 NPL

The combined standard uncertainty in the mass of each weight has been calculated by estimating an uncertainty for each of the identified contributing factors and combining these contributions in quadrature, in accordance with the 'ISO guide to the expression of uncertainty in measurement' [7], to give a combined standard uncertainty at a coverage factor of k=1.

4.1.1 Air Density

The combined standard uncertainty in the air density measurement is made up of the standard uncertainty due to each of the measured parameters, as well as the standard uncertainty from the empirical equation. The standard uncertainty associated with the equation is estimated to be $\pm$ 0.000 12 kg m^{-3}[8], which when added in quadrature to the uncertainties in the measured parameters, gives a combined standard uncertainty of $\pm$ 0.000 90 kg m^{-3} in the air density measurement at a k=1 coverage factor. The combined standard uncertainty contribution arising from the air density measurement is always less than $\pm$ 0.01 µg.

4.1.2 Mass Standards

The standards used in the calibration of the set each have a standard uncertainty of $\pm$ 0.000 05 mg assigned to them at the time of their calibration. These are all derived from the standard uncertainty of $\pm$ 0.002 7 mg assigned to the UK National Prototype Kilogram No 18. This standard uncertainty includes an element for the uncertainty in the mass gain model [9]. A component to allow for the drift in the values of the mass standards is included in their standard uncertainties.

4.1.3 Density of the weights

The estimated standard uncertainty arising from the assumed density of the standards and the weights being calibration is $\pm$ 10 kg m^{-3}. This leads to an associated standard uncertainty of $\pm$ 0.000 02 mg in the mass values assigned to the weights.

Weighing Scheme

The weighing scheme used allows for a redundancy of data. The standard uncertainty for each weight in the weighing scheme is calculated by a least squares analysis [5].

4.1.5 Balance

The NPL convention is to take the standard uncertainty of the balance to be equal to the standard deviation of twenty consecutive readings that have been carried out during its assessment. However, it may be considered that the balance standard uncertainty is equal to the estimated standard uncertainty of twenty consecutive readings (ie the standard deviation divided by $\sqrt{n-1}$), which gives a more optimistic uncertainty value.

4.2 DFM

The standard uncertainties of the measured masses have been estimated as described in ref. [6], which is consistent with the principles laid down in the *Guide* [7]. The following sources of uncertainty were considered.

Value of reference mass

Based on the calibration history the mass of W1g was set to 1 g + 0.000 89 mg with a standard uncertainty of ± 0.000 7 mg.

Air Density

As described in a previous section, the standard uncertainty of the air density has been estimated to ± 0.000 11 kg m^{-3}. The relative standard uncertainty of the recommended formula itself has been estimated to ± 6.5 E-5, corresponding to a standard uncertainty of ± 0.000 08 kg m^{-3} in the calculated air density, which is included in the above estimate.

Volumes of weights

The volumes assigned to the DFM weights have been based on either hydrostatic weighing of the particular weight, or calculated from assumed densities for the weight materials. The volumes of the NPL W65 weights and the associated standard uncertainties have been calculated from density value 8050 kg m^{-3} and standard uncertainty ± 10 kg m^{-3} specified by NPL.

4.2.4 Centres of gravity of weights

The vertical position of the gravity centres of the NPL W65 weights were assumed to be rectangularly distributed within ± 0.5 mm.

4.2.5 Balance repeatability

For each decade the standard deviation of a single mass difference measurement (using the *ABBA* weighing sequence) was calculated from the residuals of the least squares fit performed. This standard deviation was propagated to a standard uncertainty for each weight in the decade.

4.2.6 Scale factor

Before the calibration was carried out, the scale factor of the mass comparator were measured to be 0.999 9 mg/div with a standard uncertainty of ± 0.000 2 mg/div.

5 RESULTS

The data relating to the atmospheric conditions during the measurements are given in Table 1.

The dates and results of all the calibrations made at NPL and DFM are given in Table 2.

The differences between the mass values obtained by NPL and those obtained by DFM are given in Table 3. The data indicate a time-dependent loss in mass for all the weights. The graph in Figure 2 shows the differences of the results obtained by DFM in April 1996 and NPL in June 1996 from the results obtained by NPL in January 1996. It also illustrates the trend with which the weights are drifting. This trend is also supported by the results of the two previous calibrations made by NPL in February 1994 and March 1995. The results obtained by NPL in June 1996 agree more closely with the DFM results than the January 1996 results. This is may be due to the fact that the weights had travelled, after the first set of measurements were made, by an indirect route including a five day stay in a hotel where the atmospheric conditions are not ideal. The effect of drift in the mass values of the weights may be considerably reduced by taking an average value from the two NPL calibrations and comparing these values with the results obtained by DFM. Column four of Table 3 shows the differences calculated in this manner.

The mass value assigned to the 1 mg weight in part 'C' of the set as a result of the initial calibration at NPL in January 1996 calibration is significantly different to the values assigned in the other calibrations. The weight suffered slight damage due to mishandling during this calibration. When it was calibrated by DFM the mass of the weight was comparable to the values obtained by NPL in February 1994 and March 1995. The mass values obtained by NPL in June 1996 and August 1996 agree exactly with the DFM calibration. The weight appears to have temporarily gained mass after it was damaged[1]. Throughout subsequent calculations the measurements on this weight have been ignored.

This behaviour is similar to that exhibited by a 1 kg weight that was damaged at NPL in 1994 [9]. The reason for this behaviour is not understood.

6 CONCLUSIONS

Ideally a more stable set of weights would have been used in a comparison such as this. When the drift in the mass values of the weights is taken into account there is good agreement between the two laboratories. The mass differences of sixteen out of the seventeen weights under consideration (94 %) agree to within the combined standard uncertainties (added in quadrature) of the two laboratories. A coverage factor of k=1, indicates a level of confidence of approximately 67 %. Therefore, a result in which 94 % of the measured values agree to within the combined standard uncertainties may be considered satisfactory.

The standard uncertainties of the mass values reported by DFM are smaller than those quoted by NPL for all nominal values except 0.5 gram. The NPL uncertainty budget, shown in Table 4, may be considered to be pessimistic as it includes an element for the repeatability of the balance which is based on the standard deviation of a number of repeated measurements rather than the on the estimated standard uncertainty of this assessment. If the NPL uncertainty budget is amended to include the estimated standard uncertainty of the balance performance, as shown in the final column of Table 4, the combined standard uncertainties are reduced. An assessment of the results of the comparison based on these reduced uncertainties reveals that thirteen out of seventeen weights (76 %) agree to within the combined standard uncertainty of the two laboratories. This may also be considered a satisfactory result.

The DFM uncertainty budget is shown in Table 5.

7 SUMMARY

A comparison of the calibration results achieved by NPL and DFM (the two participating laboratories) for a set of stainless steel weights of 0.5 gram to 0.001 gram has been made. The results indicate that the mass of the weights used appears to be changing with time in a predictable manner. When the measurement results are interpreted allowing for this time-dependent drift, the agreement is satisfactory when compared to the combined standard uncertainties of measurement of the two laboratories.

8 REFERENCES

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Table 1: Atmospheric Conditions During the Measurements

		Air Pressure (mbar)	Temperature (°C)	Dew Point (°C)	Carbon Dioxide (ppm)	Air Density (kg m^{-3})
NPL Jan '96	Minimum	1006.17	20.72	3.2	400	1.187 4
	Maximum	1017.08	21.58	5.3	400	1.200 4
	Uncertainty	± 0.05	± 0.01	± 0.25	± 50	± 0.000 9
DFM Apr '96	Minimum	1001	20.8	-4.9	405	1.180
	Maximum	1019	22.0	6.4	689	1.206
	Uncertainty	± 0.05	± 0.006	± 0.1	± 20	± 0.000 11
NPL Jun '96	Minimum	1008.53	20.88	7.6	400	1.187 1
	Maximum	1034.80	22.21	9.6	400	1.218 5
	Uncertainty	± 0.05	± 0.01	± 0.25	± 50	± 0.000 9
NPL Aug '96	Minimum	1009.74	20.84	9.2	400	1.187 6
	Maximum	1014.41	21.87	10.0	400	1.196 9
	Uncertainty	± 0.05	± 0.01	± 0.25	± 50	± 0.000 9

The uncertainties stated in this table are quoted at the coverage factor of k=1

Table 2: Results of the Mass Measurements at NPL and DFM

Nominal Mass	Shape	NPL 24/1/96 - 29/1/96		DFM 16/4/96 - 30/4/96		NPL 13/6/96 - 21/6/96		NPL 9/8/96 - 22/8/96	
		Mass	Uncertainty	Mass	Uncertainty	Mass	Uncertainty	Mass	Uncertainty
g		g	± µg	g	± µg	g	± µg	g	± µg
0.5 C		0.500 006 7	0.4	0.500 005 2	0.4	0.500 004 4	0.4	0.500 004 7	0.4
0.5 D		0.499 995 4	0.4	0.499 994 8	0.4	0.499 994 4	0.4		
0.2 C		0.200 000 9	0.3	0.200 000 0	0.2	0.200 000 1	0.4	0.199 999 5	0.4
0.2 D		0.199 999 8	0.3	0.199 999 1	0.2	0.199 999 2	0.4		
0.1 C		0.100 000 0	0.3	0.099 999 2	0.2	0.099 998 7	0.4	0.099 998 7	0.4
0.1 D		0.099 987 2	0.3	0.099 986 1	0.2	0.099 986 2	0.4		
0.05 C		0.050 017 1	0.3	0.050 016 4	0.1	0.050 016 3	0.4	0.050 016 3	0.4
0.05 D		0.050 010 5	0.3	0.050 010 1	0.1	0.050 009 5	0.4		
0.02 C		0.020 008 9	0.3	0.020 008 6	0.1	0.020 008 3	0.4	0.020 008 6	0.4
0.02 D		0.020 006 8	0.3	0.020 006 3	0.1	0.020 006 5	0.4		
0.01 C		0.010 001 4	0.3	0.010 001 3	0.1	0.010 001 2	0.4	0.010 001 2	0.4
0.01 D		0.009 995 5	0.3	0.009 995 1	0.1	0.009 994 8	0.4		
0.005 C		0.005 004 1	0.3	0.005 003 9	0.1	0.005 003 8	0.4	0.005 003 7	0.4
0.005 D		0.005 005 0	0.3	0.005 004 9	0.1	0.005 004 4	0.4		
0.002 C		0.002 003 1	0.3	0.002 003 0	0.1	0.002 003 0	0.4	0.002 002 9	0.4
0.002 D		0.002 001 5	0.3	0.002 001 4	0.1	0.002 001 4	0.4		
0.001 C		0.000 998 6	0.3	0.000 997 0	0.1	0.000 997 0	0.4	0.000 997 0	0.4
0.001 D		0.001 001 1	0.3	0.001 000 9	0.1	0.001 000 6	0.4		

The uncertainties stated in this table are quoted at the coverage factor of k=1

Table 3: Comparison of Results Obtained at NPL and DFM

Nominal Mass g	Difference between NPL & DFM (Jan) & (Apr) µg	Difference between DFM & NPL (Apr & Jun) µg	Difference between NPL and DFM (allowing for drift) µg	Combined Standard Uncertainty DFM & NPL µg
0.5 C	1.5	0.8	0.35	0.6
0.5 D	0.6	0.4	0.10	0.6
0.2 C	0.9	-0.1	0.50	0.5
0.2 D	0.7	-0.1	0.40	0.5
0.1 C	0.8	0.5	0.15	0.5
0.1 D	1.1	-0.1	0.60	0.5
0.05 C	0.7	0.1	0.30	0.5
0.05 D	0.4	0.6	-0.10	0.5
0.02 C	0.3	0.3	0.00	0.5
0.02 D	0.5	-0.2	0.35	0.5
0.01 C	0.1	0.1	0.00	0.5
0.01 D	0.4	0.3	0.05	0.5
0.005 C	0.2	0.1	0.05	0.5
0.005 D	0.1	0.5	-0.20	0.5
0.002 C	0.1	0.0	0.05	0.5
0.002 D	0.1	0.0	0.05	0.5
0.001 C	1.6*	0.0*	0.80*	0.5*
0.001 D	0.2	0.3	-0.05	0.5

The uncertainties stated in this table are quoted at the coverage factor of k=1

* This weight was damaged during the January 1996 calibration at NPL.

Table 4: NPL Uncertainty Budget for NPLW65

	Standard uncertainty of contributing factors								
Nominal mass g	Standards µg	Weighing scheme µg	Balance Repeatability µg	Balance Resolution µg	Air Density µg	Density of Standard µg	Density of Test Weight µg	Combined Standard Uncertainty µg	*Revised Combined Standard Uncertainty µg
0.5	0.215	0.095	0.30	0.05	0.001 53	0.048	0.092	0.40	0.3
0.2	0.086	0.12	0.30	0.05	0.000 63	0.019	0.036	0.35	0.2
0.1	0.043	0.115	0.30	0.05	0.000 36	0.009	0.018	0.33	0.2
0.05	0.021 5	0.12	0.30	0.05	0.000 18	0.005	0.009	0.33	0.2
0.02	0.008 6	0.115	0.30	0.05	0.000 09	0.002	0.004	0.33	0.2
0.01	0.004 3	0.105	0.30	0.05	0.000 07	0.001 0	0.002	0.33	0.2
0.005	0.002 15	0.115	0.30	0.05	0.000 04	0.000 5	0.000 9	0.33	0.2
0.002	0.000 86	0.13	0.30	0.05	0.000 05	0.000 2	0.000 4	0.34	0.2
0.001	0.000 43	0.115	0.30	0.05	0.000 03	0.000 1	0.000 2	0.33	0.2

The uncertainties stated in this table are quoted at the coverage factor of k=1

Combined standard uncertainty including an estimated standard uncertainty of the balance repeatability instead of a standard deviation of the balance repeatability

Table 5: DFM Uncertainty Budget for NPLW65

	Standard uncertainty of contributing factors						
Weight	Restraint [µg]	Air density [µg]	Volume [µg]	Centre of gravity [µg]	Balance [µg]	Scale factor [µg]	Combined [µg]
C 0.5g	0.35	0.000 092	0.18	0.000 052	0.12	0.000 35	0.41
D 0.5g	0.35	0.000 092	0.18	0.000 052	0.18	0.001 7	0.43
C 0.2g	0.14	0.000 037	0.071	0.000 021	0.096	0.000 28	0.18
D 0.2g	0.14	0.000 037	0.070	0.000 021	0.14	0.000 45	0.21
C 0.1g	0.070	0.000 018	0.035	0.000 010	0.10	0.000 31	0.13
D 0.1g	0.070	0.000 018	0.035	0.000 010	0.15	0.002 9	0.17
C 0.05g	0.065	0.000 085	0.005 6	0.000 002 7	0.079	0.004 3	0.10
D 0.05g	0.10	0.000 085	0.005 6	0.000 002 7	0.066	0.004 0	0.12
C 0.02g	0.026	0.000 034	0.003 7	0.000 001 8	0.093	0.001 3	0.096
D 0.02g	0.040	0.000 034	0.003 7	0.000 001 8	0.078	0.001 2	0.088
C 0.01g	0.013	0.000 017	0.002 0	0.000 000 97	0.10	0.001 2	0.10
D 0.01g	0.020	0.000 017	0.002 0	0.000 000 97	0.087	0.002 2	0.090
C 0.005g	0.050	0.000 008 4	0.000 72	0.000 000 27	0.038	0.003 7	0.063
D 0.005g	0.050	0.000 008 4	0.000 71	0.000 000 27	0.059	0.003 9	0.078
C 0.002g	0.020	0.000 003 4	0.000 57	0.000 000 18	0.045	0.001 2	0.049
D 0.002g	0.020	0.000 003 4	0.000 56	0.000 000 18	0.070	0.001 6	0.073
C 0.001g	0.010	0.000 001 7	0.000 51	0.000 000 097	0.050	0.001 5	0.051
D 0.001g	0.010	0.000 001 7	0.000 51	0.000 000 097	0.078	0.000 79	0.079

The uncertainties stated in this table are quoted at the coverage factor of k=1

Table 6: Mass values obtained for the added NPL weights in part 'C' of NPLW65 together with the values obtained in April 1996 when the set NPLW54 was last calibrated

			Calibration from NPLW65 C		Calibration from NPLW54	
Identification NPLW 54	Density kg m^{-3}	Uncertainty ± kg m^{-3}	Aug 1996 mg	Uncertainty ± mg	Apr 1996 mg	Uncertainty ± mg
0.2D g	7 840	30	-0.008 8	0.000 2	-0.009 0	0.002 4
0.1D g	7 840	30	+0.019 7	0.000 1	+0.019 8	0.001 2
0.02D g	7 840	30	-0.003 0	0.000 2	-0.003 2	0.000 7
0.01D g	7 840	30	+0.010 4	0.000 2	+0.010 6	0.000 8
0.002D g	2 700	50	+0.007 0	0.000 1	+0.007 1	0.000 4
0.001D g	2 700	50	-0.004 4	0.000 1	-0.004 3	0.000 4

Table 7: Mass corrections obtained for the added DFM weights together with average values obtained since 1992

			NPL W65 C		NPL W65 D		History	
Identification	Density kg m^{-3}	Uncertainty ± kg m^{-3}	Apr 1996 mg	uncertainty ± mg	Apr 1996 mg	Uncertainty ± mg	E(*Dm*) mg	s(*Dm*) mg
DFM 388 R1g	7 833.006	0.031	-0.002 9	0.000 8	-0.003 2	0.000 8	-0.003 2	0.000 6
DFM 387 R200mg	21 400	90	-0.018 3	0.000 2	-0.018 3	0.000 2	-0.017 0	0.001 4
DFM 387 R100mg	21 400	90	-0.007 8	0.000 1	-0.007 9	0.000 1	-0.007 3	0.000 5
DFM 387 R20mg	21 400	90	+0.047 1	0.000 1	+0.047 1	0.000 1	+0.047 7	0.000 4
DFM 387 R10mg	21 400	90	-0.002 8	0.000 1	-0.002 8	0.000 1	-0.002 7	0.000 3
DFM 386 R2mg	21 400	90	+0.041 0	0.000 05	+0.041 1	0.000 1	+0.041 5	0.000 2
DFM 386 R1mg	21 400	90	+0.069 8	0.000 1	+0.070 0	0.000 1	+0.070 0	0.000 14
DFM 216 A1mg	21 400	90	+0.002 7	0.000 1	+0.002 8	0.000 1	+0.002 9	0.000 2

Figure 1: Traceability of PI Grams and NPLW 43

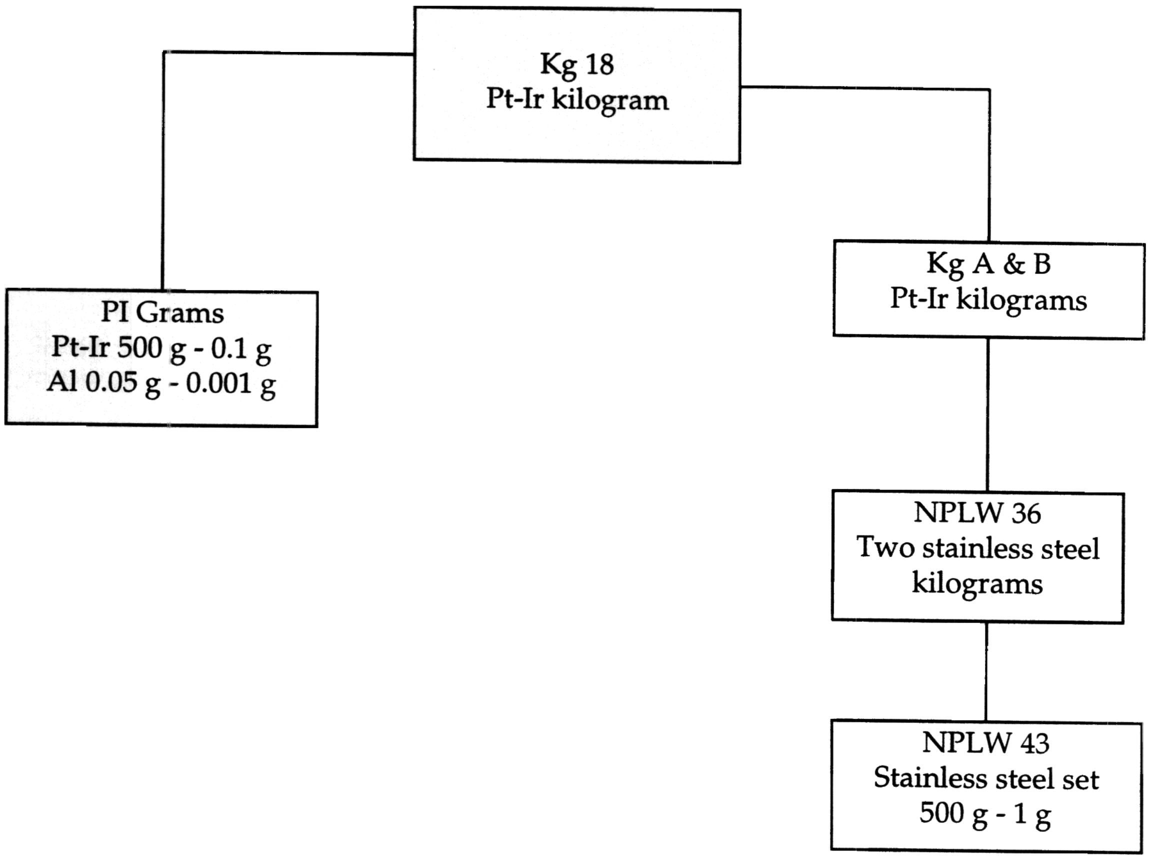

Figure 2. Graph showing the change in measured mass for NPLW65 in April 1996 and June 1996 relative to the values measured in January 1996