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Intercomparison of force standards between NPL and CSIRO

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Abstract

This report describes the NPL-piloted intercomparison of compressive force measurements between: Commonwealth Scientific and Industrial Research Organisation (CSIRO), New South Wales, Australia; and National Physical Laboratory (NPL), Teddington, United Kingdom. Forces were measured in the range from 50 N to 5 kN during the period from 1 March 1999 to 14 June 1999. The results showed that the forces generated by each of the laboratories' deadweight force standard machines agreed between -0.005 % and +0.009 3 % for increasing forces, and between -0.035 8 % and +0.010 % for decreasing forces. The agreement between the machines when the load cells calibrated range is restricted to between 40 % and 100 % of its maximum capacity is far greater; i.e. between -0.003 8 % and +0.006 6 % for increasing forces, and between -0.009 8 % and +0.007 5 % for decreasing forces. The agreements were all within the calculated uncertainties of measurement.

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Approved on behalf of the Managing Director, NPL,
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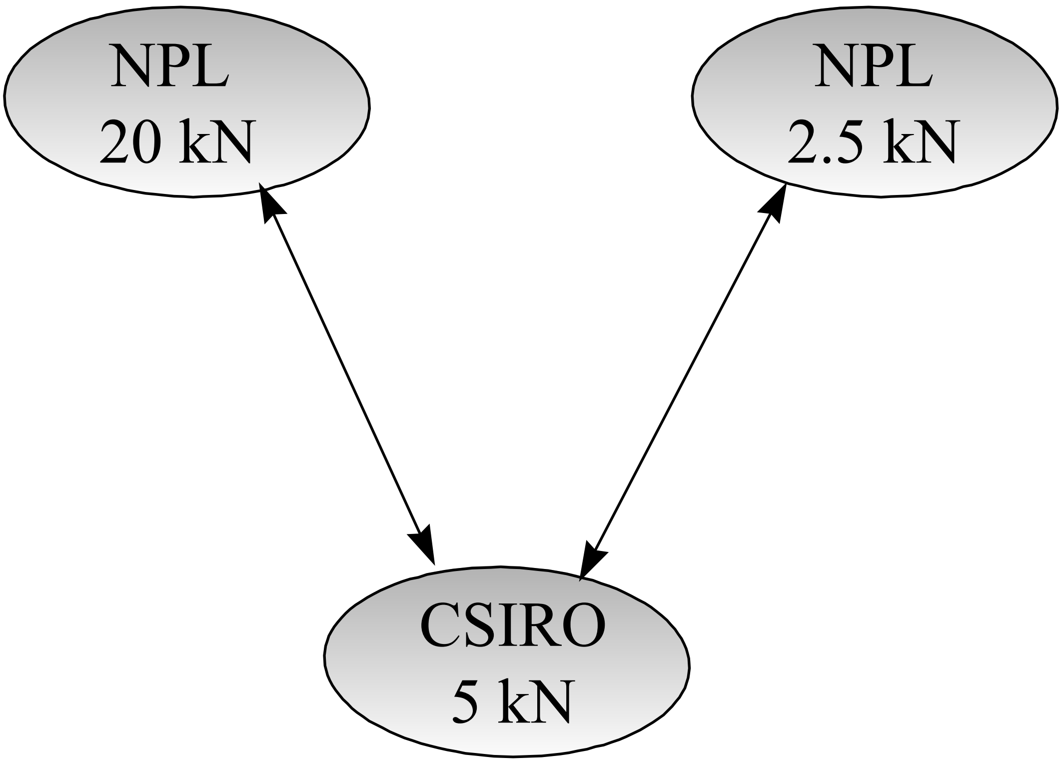
1. Introduction

Accurate and traceable force measurements are essential in many areas of engineering and commerce. In most countries, a national measurement institute (NMI) is responsible for realising and disseminating the newton, the SI unit of force. The NMI will maintain a series of force standard machines capable of generating known forces. These machines are used to calibrate force transducers used in industry as secondary standards.

It is important that NMIs intercompare their standard machines so that measurements made in different countries are consistent. This is of fundamental importance to many areas of international trade. An intercomparison was therefore carried out between the NMIs of the UK (NPL) and Australia (CSIRO).

All uncertainties quoted in this document are based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %[1 & 2].

The intercomparisons between the force standard machines are illustrated below. The measurements were made in the following order - NPL then CSIRO then NPL again. The solid lines therefore represent full intercomparisons with pre and post measurements at NPL.



2. Force standard machines

Deadweight force standard machines were used in this intercomparison.

Deadweight force standard machines are so called because the forces are generated by a series of known masses in a known gravitational field. The force is calculated using the following equation:

$$F = m_c\, g \left(1 - \frac{1.2}{8\ 000} + \frac{\left(1.2 - \rho_a\right)}{\rho_w} \right)$$

where m_c is the conventional mass of the weight, g is the local gravitational acceleration, ρ_a is the air density, and ρ_w is the density of the weight.

The forces are traceable to the base SI units of mass, length, and time.

2.1 NPL 20 kN deadweight force standard machine

The NPL 20 kN deadweight force standard machine was installed in 1987. The machine is designed to apply incremental and decremental forces to force transducers (usually load cells), in either tension or compression. It comprises four main elements :

- a loading platen to support the force transducer;
- a scalepan made from austenitic stainless steel with yokes for supporting stainless steel deadweights;
- 24 austenitic stainless steel deadweights which can be applied to the scalepan to generate the required force;
- a fixed framework on solid foundations.

2.1.1 Operational procedure

In compression calibrations, the load cell, with a self-aligning fitting, is placed centrally on the hardened steel loading pad on the top of the loading platen. The clearance between the scalepan and the load cell's self-aligning fitting needs to be approximately 10 mm; this is achieved by locating blocks of differing thicknesses between the loading pad and the loading platen. The scalepan is lowered onto the load cell by a drive motor. A second drive motor lowers the deadweight support mechanism applying the deadweights to the scalepan by a yoke and pin assembly. Specific forces are applied to the load cell through the scalepan by lowering the deadweight support mechanism so that the appropriate number of deadweights are on the scalepan.

2.1.2 Deadweights

The 24 austenitic stainless steel weights were calibrated against standards of known mass and density at NPL in 1988[4]. Three of the deadweights were removed from the machine and re-weighed during November 1998[3], a full calibration of the deadweights being deferred until after the relocation of the machine in the summer of 2000. (The uncertainty associated with the conventional masses of the NPL deadweights is within ±2 ppm). The conventional mass values required to generate each of the nominal forces were calculated and trim weights were attached to the deadweights to make up the difference between the actual mass and the required mass. This process resulted in masses within ±2 ppm of the required conventional values.

The nominal forces generated by the scalepan and the weights comprise of ten 0.5 kN increments then fifteen 1.0 kN increments.

The claimed uncertainty of the forces applied by the machine is[3&4]:

±0.001 % in the range from 0.5 kN to 20 kN

2.2 NPL 2.5 kN deadweight force standard machine

The NPL 2.5 kN deadweight force standard machine was commissioned in 1997. The machine is designed to apply incremental and decremental forces to force transducers (usually load cells), in either tension or compression. It comprises four elements :

- a loading platen to support the force transducer;
- a stainless steel scalepan with yokes for supporting the deadweights;
- 1 titanium and 29 austenitic stainless steel deadweights which can be applied to the scalepan to generate the required force;
- a fixed framework on solid foundations.

2.2.1 Operational procedure

In compression calibrations, the load cell, with a self-aligning fitting, is placed centrally on the hardened steel block on the top of the loading platen. The loading platen is driven up or down until there is approximately 10 mm clearance between the load cell's self-alignment fitting and the scalepan. The scalepan is lowered onto the load cell by three synchronised drive motors. Three further synchronised drive motors lower the deadweight support mechanism, applying the deadweights to the scalepan by a yoke and pin assembly. Specific forces are applied to the load cell through the scalepan by lowering the deadweight support mechanism so that the appropriate number of weights are on the scalepan.

2.2.2 Deadweights

The scalepan, 1 titanium and 29 austenitic stainless steel weights were calibrated against standards of known mass and density at NPL in 1997. (The uncertainty associated with the conventional masses of the NPL deadweights is within ±2 ppm). The conventional mass values required to generate each of the nominal forces were calculated and trim weights were attached to the deadweights to make up the difference between the actual mass and the required mass. This process resulted in masses within ±2 ppm of the required conventional values.

The nominal forces generated by the scalepan and the weights comprise of two 25 N increments then nine 50 N increments and twenty 100 N increments.

The claimed uncertainties of the forces applied by the machine are[5]:

±0.001 % in the range from 25 N to 2.5 kN

2.3 CSIRO 5 kN deadweight force standard machine

The Morehouse 5 kN deadweight force standard machine was installed in the early 1980s at the National Measurement Laboratory in Sydney, Australia. The machine is designed for the application of incremental and decremental forces to force transducers (usually load cells), in either tension or compression. It comprises four main elements :

- a loading stage to support the force transducer;
- a yoke assembly with a weight rod for the application of forces;
- 18 stainless steel deadweights which can applied manually to a weight rod to generate the required force;
- a fixed framework on solid foundations.

2.3.1 Operational procedure

In compression calibrations, the load cell, with a self-aligning fitting, is placed centrally on the hardened steel block on the top of the adjustable loading stage, directly under the conical ball seat of the upper yoke to ensure proper axial alignment. The loading stage is adjusted so that there is approximately 10 mm clearance between the load cell and the upper yoke. The yoke assembly is lowered onto the load cell by lifting the yoke lever. The weight levers that actuate the weight support mechanisms are turned which removes the supports from the deadweights and applies the deadweights to the yoke assembly weight rod. Specific deadweights are applied to the load cell through the yoke assembly by turning the appropriate weight levers. During the calibration, regular checks are needed to ensure that the deadweights resting on the weight supports are not in contact with the centrally mounted weight rod.

2.3.2 Deadweights

The yoke assembly and the 18 stainless steel weights were calibrated against standards of known mass and density at NML in 1996. (The uncertainty associated with the conventional masses of the Morehouse weights is within ±3 ppm). The conventional mass values required to generate each of the nominal forces were calculated and trim weights were attached to the deadweights to make up the difference between the actual mass and the required mass. This process resulted in masses within ±2 ppm of the required conventional values.

The nominal forces generated by the scalepan and the weights allow any 5 N increment from 50 N to 5.665 kN.

The claimed uncertainty of the forces applied by the machine is:

±0.002 % in the range from 50 N to 5.5 kN.

3. Intercomparison equipment

Three strain gauge load cells were used in the intercomparison, the details of which are shown in Table 1.

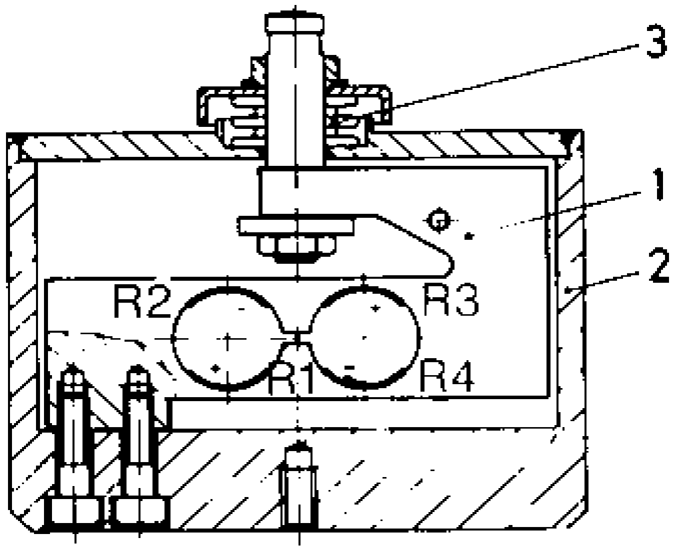
Table 1

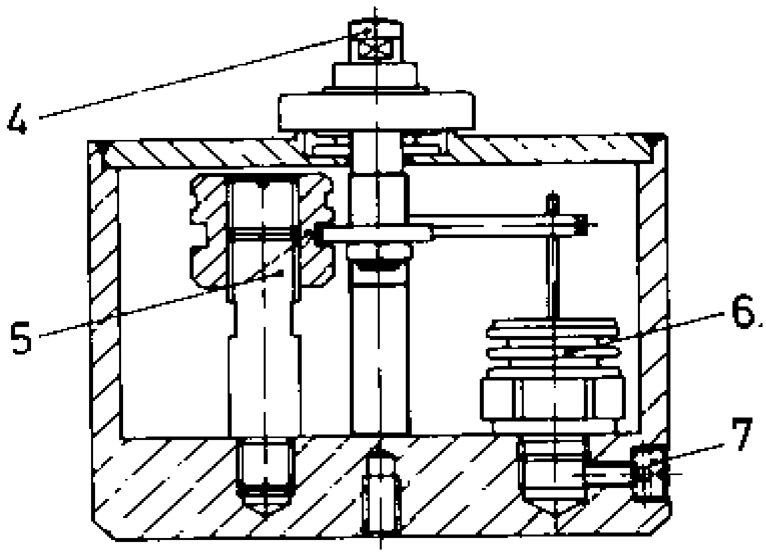
Capacity	Serial number	Manufacturer
1 kN	C28916	Interface Inc.
2.5 kN	A56599	Interface Inc.
5 kN	E28311	Hottinger Baldwin Messtechnik (HBM)

The HBM load cell has a hermetically sealed cylindrical steel casing enclosing a measuring spring element. To prevent the casing absorbing any force, the measuring spring element is attached to the case by a diaphragm. Strain gauges are bonded to the surface of the measuring spring element (Figure 1). The load cell is equipped with an overload protection mechanism, and can withstand an overload of 150% of its rated capacity. The load cell has a domed upper loading button, on to which a soft steel pad is centrally placed.

The two Interface load cells each have a casing enclosing a bending beam element with strain gauges bonded to the surface of the beam element (Figure 2). They are each used with their own locating ball seating unit and lower loading pad.

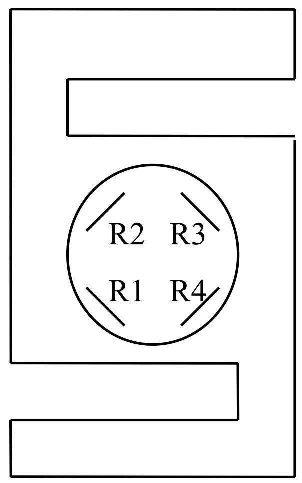
The output voltage ratios from each load cell were measured by an HBM precision AC ratio meter, (type DMP 39, serial number 102).





Key	1	Measuring spring	2	Hermetically sealed casing
	3	Diaphragm	4	Load button
	5	Overload protection	6	Atmospheric pressure compensation
	7	Bleed screw	R1 to R4	Strain gauges

Figure 1: Cylindrical measuring spring load cell



Key R1 to R4 Strain gauges

Figure 2: ‘S’ type bending beam load cell

4. Test procedure

4.1 Positioning of the load cells in the force standard machines

The 2.5 kN and 1 kN load cells were each supplied with their own ball seating unit and loading pad, which located in the loading surfaces of the load cell.

The 5 kN load cell was mounted on a loading pad. A steel pad of hardness less than 300 HV, was placed centrally on the loading button.

Each load cell was centred in each machine used, to ensure that the force was applied uniaxially.

4.2 Loading and timing sequences

All of the measurements were made following a timed loading sequence to minimise the effects of creep. This loading sequence is illustrated in Figure 3. Following a change of applied force, no readings are taken for a period of two minutes.

Each measurement series was made up of seven runs. After the first two runs, each load cell was rotated through 120°. A further two runs were performed. This process was repeated after rotating the load cells to the 240° position. Finally, the load cells were rotated to the 360° position and a seventh run was carried out. Before starting each measurement series, the load cell was preloaded five times to the maximum force to be applied. After each rotation, the load cell was preloaded three times to the maximum force to be applied.

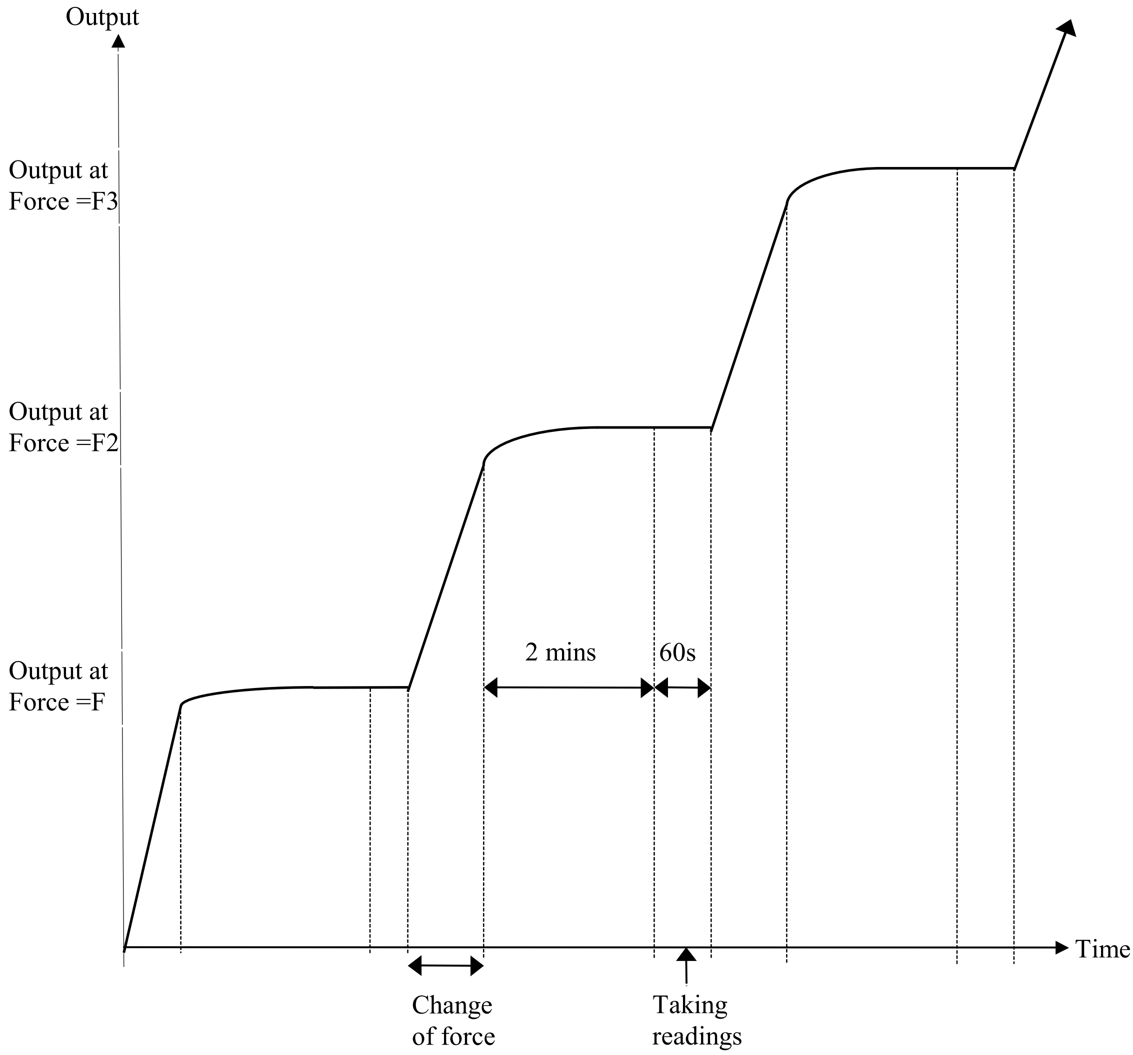


Figure 3: Timed loading sequence

5. Results obtained in the NPL deadweight force standard machines

Sections 5.1, 5.2, and 5.3 contain a summary of the measurements made at NPL both before (pre) and after (post) the measurements made at CSIRO. They show the unbiased mean output ratios measured at each force both incrementally and decrementally.

As described above, three measurements are made at the 0° / 360° position, and two at each of the other two rotations. The unbiased mean output ratio was calculated by averaging the mean values obtained at each of the three positions. The overall mean output ratio at each force was then calculated by averaging the pre and post mean output ratios. The drift of the load cell between the calibrations at NPL was calculated using[6]:

$$\text{Drift contribution} \;=\; \frac{100}{\sqrt{3}} \times \left(\frac{\text{post - pre}}{\text{overall mean}} \right) \text{ expressed as a percentage}$$

The divisor of √3 is included because this distribution is treated as rectangular.

The reproducibility was calculated from the standard deviation of the mean output ratios at each rotational position. The repeatability was calculated from the mean of the standard deviations at each rotational position. The uncertainty of the mean output ratio at each force was calculated by combining in quadrature the reproducibility and repeatability and then subtracting the uncertainty of the forces generated by the NPL deadweight force standard machine. The uncertainty of each overall mean output ratio was calculated using

$$\text{Overall uncertainty } = 2 \times \sqrt{\left(\frac{\text{pre uncertainty} + \text{post uncertainty}}{4} \right)^2 + \text{drift}^2}$$

The expanded uncertainty is expressed as a percentage.

The minimum uncertainty that can be assigned to measurements is that of the forces generated by the NPL deadweight force standard machines.

5.1 5 kN load cell calibrated in NPL's 20 kN machine

Nominal Force	Pre		Post			Overall Mean	
	Mean Output	Uncertainty	Mean Output	Uncertainty	Drift	Output	Uncertainty
kN	mV/V	%	mV/V	%	%	mV/V	%
0.5	0.203 856	0.001 6	0.203 834	0.002 2	-0.006 5	0.203 844	0.013 0
1.0	0.407 732	0.000 9	0.407 698	0.001 0	-0.004 7	0.407 716	0.009 4
2.0	0.815 522	0.001 0	0.815 472	0.001 0	-0.003 6	0.815 496	0.007 3
3.0	1.223 352	0.000 7	1.223 288	0.001 0	-0.003 0	1.223 320	0.006 1
4.0	1.631 250	0.000 4	1.631 184	0.001 0	-0.002 4	1.631 218	0.004 7
5.0	2.039 238	0.001 0	2.039 180	0.001 0	-0.001 7	2.039 210	0.003 5
4.0	1.631 338	0.000 9	1.631 256	0.001 0	-0.002 9	1.631 296	0.005 9
3.0	1.223 466	0.000 8	1.223 402	0.001 0	-0.003 1	1.223 434	0.006 3
2.0	0.815 640	0.001 0	0.815 592	0.001 0	-0.003 6	0.815 616	0.007 1
1.0	0.407 822	0.001 4	0.407 778	0.001 0	-0.006 2	0.407 800	0.012 4
0.5	0.203 906	0.002 8	0.203 880	0.001 9	-0.007 2	0.203 894	0.014 6

5.2 2.5 kN load cell calibrated in NPL's 2.5 kN machine

Nominal Force	Pre		Post			Overall Mean	
	Mean Output	Uncertainty	Mean Output	Uncertainty	Drift	Output	Uncertainty
kN	mV/V	%	mV/V	%	%	mV/V	%
0.25	0.360 826	0.015 7	0.360 874	0.019 1	0.007 9	0.360 850	0.023 4
0.50	0.721 702	0.019 4	0.721 758	0.034 2	0.004 6	0.721 730	0.028 3
1.00	1.443 552	0.027 9	1.443 518	0.040 2	-0.001 4	1.443 534	0.034 2
1.50	2.165 532	0.022 8	2.165 260	0.029 7	-0.007 3	2.165 396	0.030 0
2.00	2.887 574	0.020 0	2.887 142	0.027 4	-0.008 7	2.887 358	0.029 3
2.50	3.609 572	0.016 4	3.609 058	0.023 7	-0.008 3	3.609 316	0.025 9
2.00	2.887 940	0.013 7	2.887 556	0.022 6	-0.007 7	2.887 748	0.023 8
1.50	2.166 082	0.010 0	2.165 826	0.018 3	-0.006 9	2.165 954	0.019 7
1.00	1.444 048	0.006 7	1.444 058	0.019 3	0.000 4	1.444 052	0.013 0
0.50	0.721 936	0.006 2	0.722 112	0.022 0	0.014 1	0.722 024	0.031 5
0.25	0.360 960	0.008 7	0.361 058	0.030 0	0.015 6	0.361 008	0.036 7

5.3 1 kN load cell calibrated in NPL's 2.5 kN machine

Nominal Force	Pre		Post			Overall Mean	
	Mean Output	Uncertainty	Mean Output	Uncertainty	Drift	Output	Uncertainty
N	mV/V	%	mV/V	%	%	mV/V	%
50	0.160 992	0.037 2	0.160 988	0.018 9	-0.001 0	0.160 990	0.028 1
100	0.321 978	0.006 8	0.321 984	0.032 0	0.001 3	0.321 982	0.019 6
200	0.644 010	0.019 7	0.644 000	0.031 1	-0.000 9	0.644 004	0.025 5
400	1.287 976	0.013 4	1.288 010	0.016 0	0.001 6	1.287 994	0.015 0
600	1.931 840	0.008 8	1.931 966	0.016 9	0.003 8	1.931 904	0.014 9
800	2.575 472	0.008 3	2.575 856	0.017 4	0.008 6	2.575 664	0.021 5
1 000	3.219 036	0.007 5	3.219 642	0.017 4	0.010 9	3.219 338	0.025 1
800	2.575 564	0.005 8	2.575 996	0.013 0	0.009 7	2.575 780	0.021 5
600	1.931 964	0.008 5	1.932 196	0.012 3	0.007 0	1.932 080	0.017 3
400	1.288 134	0.008 0	1.288 242	0.013 5	0.004 9	1.288 188	0.014 5
200	0.644 190	0.016 1	0.644 194	0.016 0	0.000 5	0.644 192	0.016 1
100	0.322 110	0.004 1	0.322 108	0.030 6	-0.000 5	0.322 108	0.017 4
50	0.161 054	0.017 9	0.161 046	0.035 2	-0.002 5	0.161 050	0.027 0

6. Results obtained in the CSIRO 5 kN machine

Sections 6.1, 6.2, and 6.3 contain a summary of the measurements made at CSIRO. Three measurements were made at the 0° / 360° position, and two at each of the other two rotations. The unbiased mean output ratio was calculated by averaging the mean values obtained at each of the three rotations. The measured deviations from the values obtained at NPL were calculated in terms of both kilonewtons and as a percentage of the nominal force. The uncertainty for each mean force was calculated using:

$$\text{Uncertainty} = 2 \times \sqrt{\text{repeatability}^2 + \text{reproducibility}^2 + \text{NPL machine unc.}^2 + \text{resolution}^2}$$

where all of the terms are the 95% uncertainty contributions.

Machines 1 and 2 agree within their uncertainty limits if:

$$\text{absolute value of} \left(\frac{\text{deviation}}{\sqrt{u_1^2 + u_2^2}} \right) < 1$$

where u_1 and u_2 are the uncertainties of each force measured by the force transducer in machines 1 and 2, or the stated uncertainties of the machines, whichever are the greater.

The bounds of the measured deviation were calculated by both adding and subtracting the uncertainty of mean output from the measured deviation.

6.1 5 kN load cell calibrated in CSIRO's 5 kN machine

Nominal Force kN	Mean Output mV/V	Measured Force kN	Measured Deviation kN	Measured Deviation %	Uncertainty Of Mean Output %	Uncertainty Min %	Uncertainty Max %	Agreement Between Machines
0.50	0.203 842	0.499 992	-0.000 008	-0.001 6	0.026 2	-0.027 7	0.024 5	YES
1.00	0.407 702	0.999 969	-0.000 031	-0.003 1	0.023 3	-0.026 4	0.020 2	YES
2.00	0.815 466	1.999 924	-0.000 076	-0.003 8	0.019 7	-0.023 4	0.015 9	YES
3.00	1.223 298	2.999 947	-0.000 053	-0.001 8	0.018 0	-0.019 7	0.016 1	YES
4.00	1.631 206	3.999 971	-0.000 029	-0.000 7	0.017 2	-0.017 9	0.016 5	YES
5.00	2.039 198	4.999 972	-0.000 028	-0.000 6	0.016 1	-0.016 6	0.015 5	YES
4.00	1.631 386	4.000 219	0.000 219	0.005 5	0.016 6	-0.011 1	0.022 0	YES
3.00	1.223 494	3.000 145	0.000 145	0.004 8	0.017 3	-0.012 4	0.022 1	YES
2.00	0.815 638	2.000 055	0.000 055	0.002 8	0.018 9	-0.016 1	0.021 7	YES
1.00	0.407 818	1.000 046	0.000 046	0.004 6	0.022 4	-0.017 7	0.027 0	YES
0.50	0.203 908	0.500 038	0.000 038	0.007 5	0.025 1	-0.017 6	0.032 6	YES

6.2 2.5 kN load cell calibrated in CSIRO's 5 kN machine

Nominal Force kN	Mean Output mV/V	Measured Force kN	Measured Deviation kN	Measured Deviation %	Uncertainty Of Mean Output %	Uncertainty Min %	Uncertainty Max %	Agreement Between Machines
0.25	0.360 836	0.249 991	-0.000 009	-0.003 5	0.029 9	-0.033 3	0.026 3	YES
0.50	0.721 690	0.499 973	-0.000 027	-0.005 5	0.023 3	-0.028 7	0.017 8	YES
1.00	1.443 588	1.000 037	0.000 037	0.003 7	0.009 2	-0.005 5	0.012 9	YES
1.50	2.165 540	1.500 100	0.000 100	0.006 6	0.006 5	0.000 2	0.013 0	YES
2.00	2.887 478	2.000 083	0.000 083	0.004 1	0.006 0	-0.001 8	0.010 1	YES
2.50	3.609 464	2.500 104	0.000 104	0.004 1	0.004 1	0.000 1	0.008 2	YES
2.00	2.887 810	2.000 044	0.000 044	0.002 2	0.006 3	-0.004 0	0.008 4	YES
1.50	2.165 930	1.499 984	-0.000 016	-0.001 1	0.034 8	-0.035 8	0.033 6	YES
1.00	1.443 910	0.999 902	-0.000 098	-0.009 8	0.037 5	-0.047 3	0.027 6	YES
0.50	0.721 838	0.499 871	-0.000 129	-0.025 8	0.049 6	-0.075 3	0.023 8	YES
0.25	0.360 880	0.249 911	-0.000 089	-0.035 8	0.043 7	-0.079 5	0.007 9	YES

6.3 1 kN load cell calibrated in CSIRO's 5 kN machine

Nominal Force N	Mean Output mV/V	Measured Force N	Measured Deviation N	Measured Deviation %	Uncertainty Of Mean Output %	Uncertainty Min %	Uncertainty Max %	Agreement Between Machines
50	0.160 990	49.999 7	-0.000 3	-0.000 5	0.034 6	-0.035 1	0.034 0	YES
100	0.322 000	100.005 8	0.005 8	0.005 8	0.010 2	-0.004 3	0.015 9	YES
200	0.644 064	200.018 6	0.018 6	0.009 3	0.009 4	-0.000 1	0.018 7	YES
400	1.288 026	400.010 0	0.010 0	0.002 5	0.031 7	-0.029 1	0.034 1	YES
600	1.931 934	600.009 6	0.009 6	0.001 6	0.032 6	-0.031 0	0.034 1	YES
800	2.575 746	800.025 2	0.025 2	0.003 2	0.039 9	-0.036 7	0.043 0	YES
1 000	3.219 468	1 000.040 1	0.040 1	0.004 0	0.037 2	-0.033 1	0.041 2	YES
800	2.575 816	800.011 1	0.011 1	0.001 4	0.037 7	-0.036 3	0.039 1	YES
600	1.932 066	599.995 5	-0.004 5	-0.000 7	0.039 2	-0.039 9	0.038 4	YES
400	1.288 174	399.995 8	-0.004 3	-0.001 1	0.026 0	-0.027 0	0.024 9	YES
200	0.644 210	200.005 3	0.005 3	0.002 7	0.033 5	-0.030 8	0.036 1	YES
100	0.322 132	100.006 9	0.006 9	0.006 9	0.033 8	-0.026 8	0.040 7	YES
50	0.161 066	50.005 0	0.005 0	0.010 0	0.054 8	-0.044 7	0.064 8	YES

7. Comparison of results obtained in the deadweight force standard machines

7.1 Comparison of results between the NPL 20 kN machine and the CSIRO 5 kN machine

7.1.1 Results using the 5 kN load cell

The four graphs compare the forces measured in the deadweight force standard machines, and show the overall uncertainties of the forces measured by the 5 kN load cell.

The first two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the 20 kN machine (see section 5.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the CSIRO 5 kN machine (see section 6.1) from those measured in the NPL 20 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the CSIRO 5 kN machine calculated using the equation in section 6.

The second two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the CSIRO 5 kN machine (see section 6.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NPL 20 kN machine (see section 5.1), from those measured in the CSIRO 5 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NPL 20 kN machine calculated using the equation in section 6.

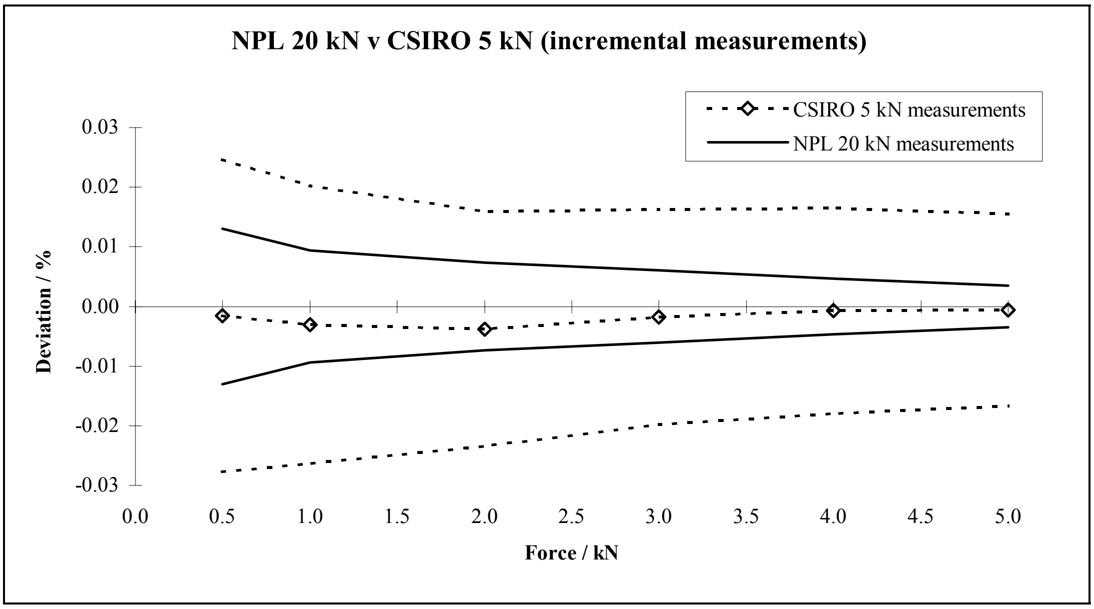


Figure 4: NPL 20 kN v CSIRO 5 kN machine for incremental forces

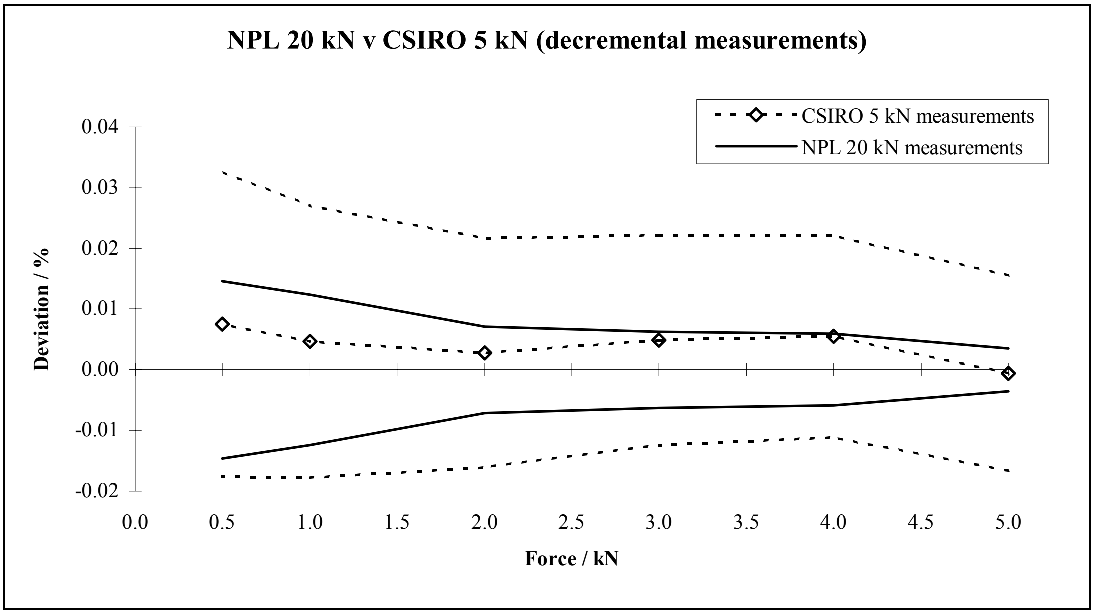


Figure 5: NPL 20 kN v CSIRO 5 kN machine for decremental forces

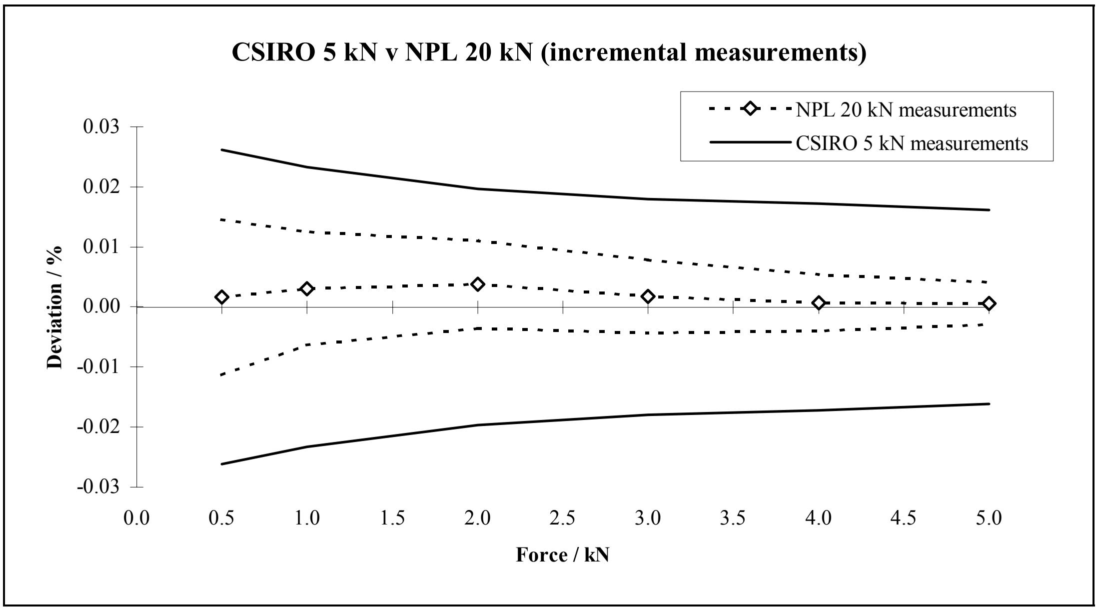


Figure 6: CSIRO 5 kN v NPL 20 kN machine for incremental forces

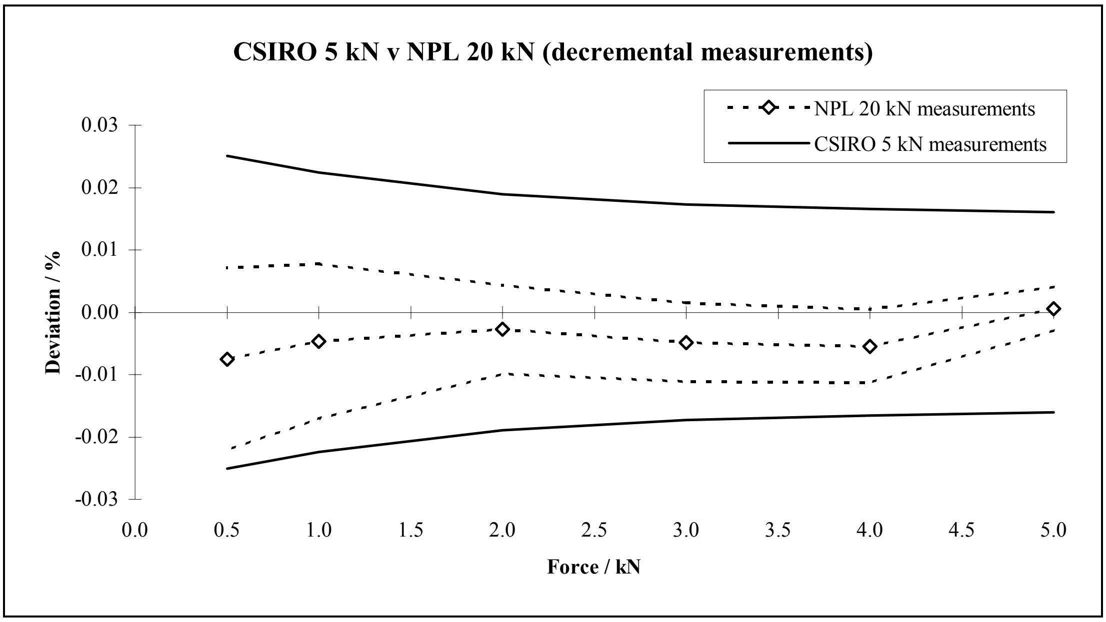


Figure 7: CSIRO 5 kN v NPL 20 kN machine for decremental forces

7.2 Comparison of results between the NPL 2.5 kN machine and the CSIRO 5 kN machine

7.2.1 Results using the 2.5 kN load cell

The four graphs compare the forces measured in the deadweight force standard machines, and show the overall uncertainties of the forces measured by the 2.5 kN load cell.

The first two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the 2.5 kN machine (see section 5.2). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the CSIRO 5 kN machine (see section 6.2) from those measured in the NPL 2.5 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the CSIRO 5 kN machine calculated using the equation in section 6.

The second two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the CSIRO 5 kN machine (see section 6.2). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NPL 2.5 kN machine (see section 5.2), from those measured in the CSIRO 5 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NPL 2.5 kN machine calculated using the equation in section 6.

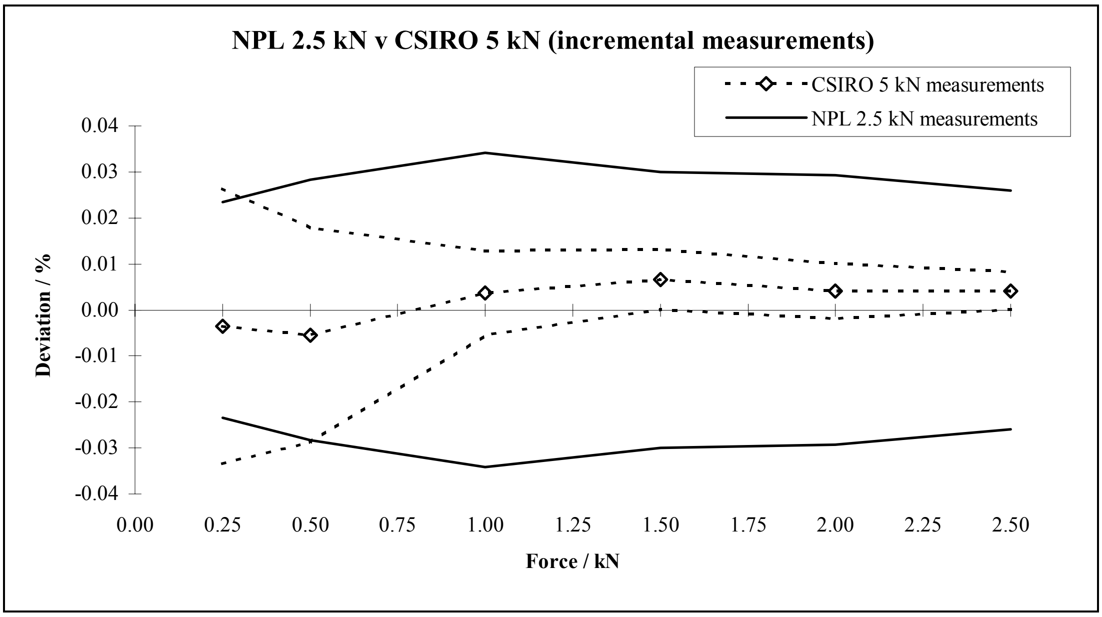


Figure 8: NPL 2.5 kN v CSIRO 5 kN machine for incremental forces

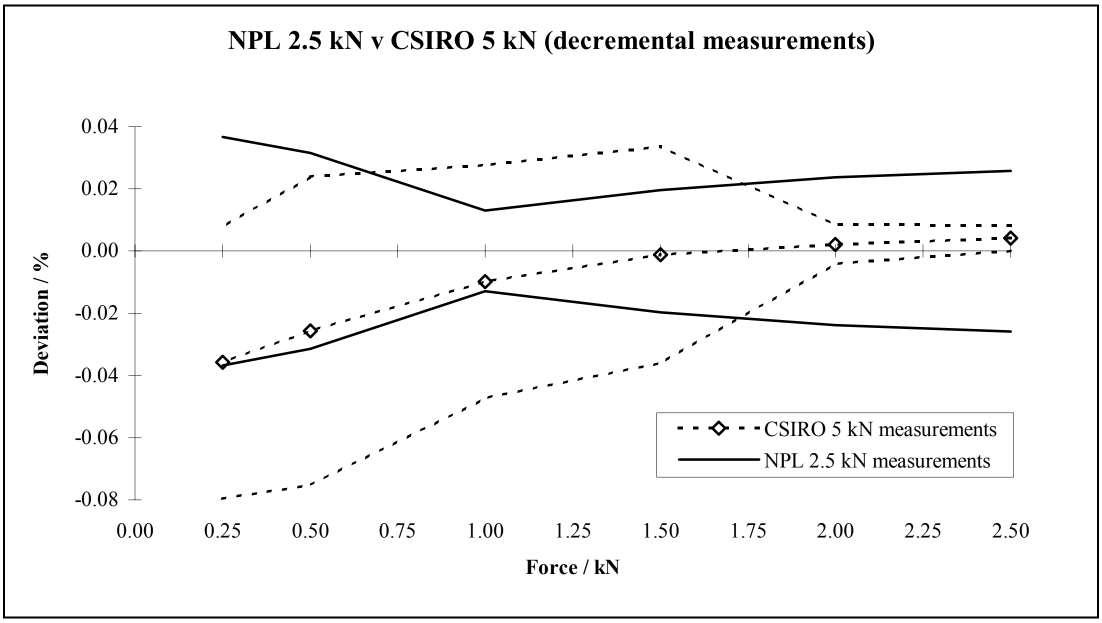


Figure 9: NPL 2.5 kN v CSIRO 5 kN machine for decremental forces

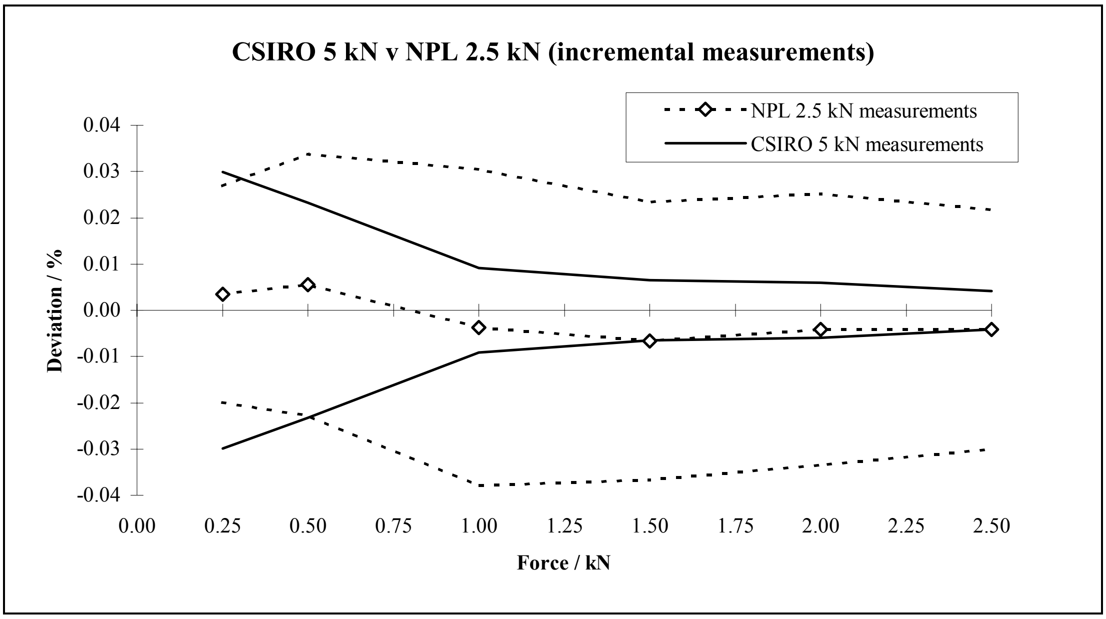


Figure 10: CSIRO 5 kN v NPL 2.5 kN machine for incremental forces

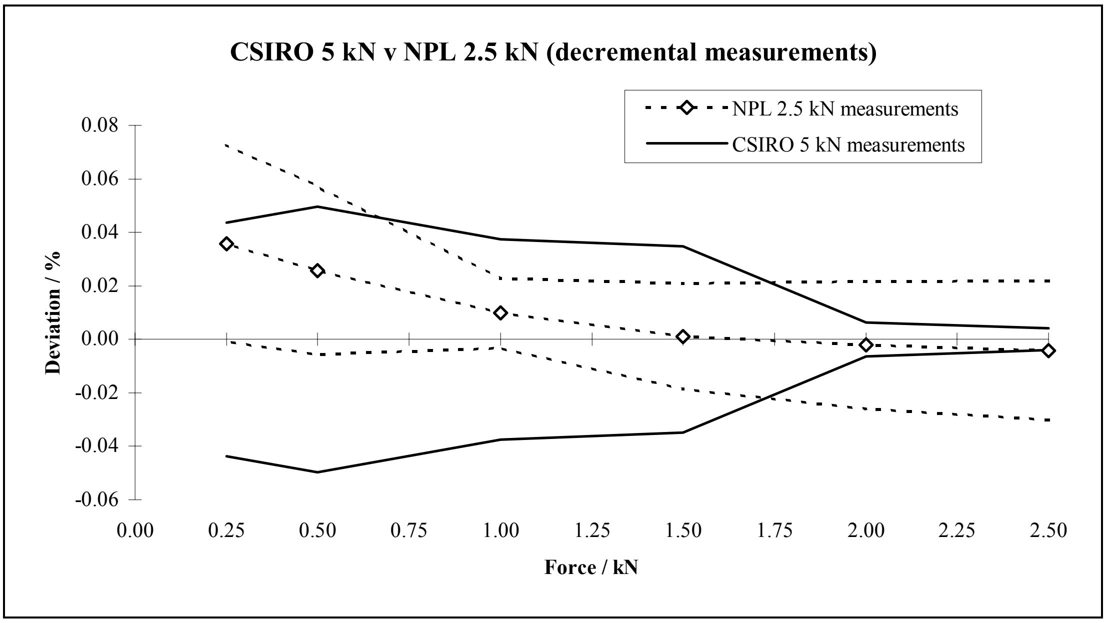


Figure 11: CSIRO 5 kN v NPL 2.5 kN machine for decremental forces

7.2.2 Results using the 1 kN load cell

The four graphs compare the forces measured in the deadweight force standard machines, and show the overall uncertainties of the forces measured by the 1 kN load cell.

The first two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the 2.5 kN machine (see section 5.3). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the CSIRO 5 kN machine (see section 6.3) from those measured in the NPL 2.5 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the CSIRO 5 kN machine calculated using the equation in section 6.

The second two graphs show the overall uncertainties of the forces measured by the load cell when calculated from the measurements made in the CSIRO 5 kN machine (see section 6.3). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NPL 2.5 kN machine (see section 5.3), from those measured in the CSIRO 5 kN machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NPL 2.5 kN machine calculated using the equation in section 6.

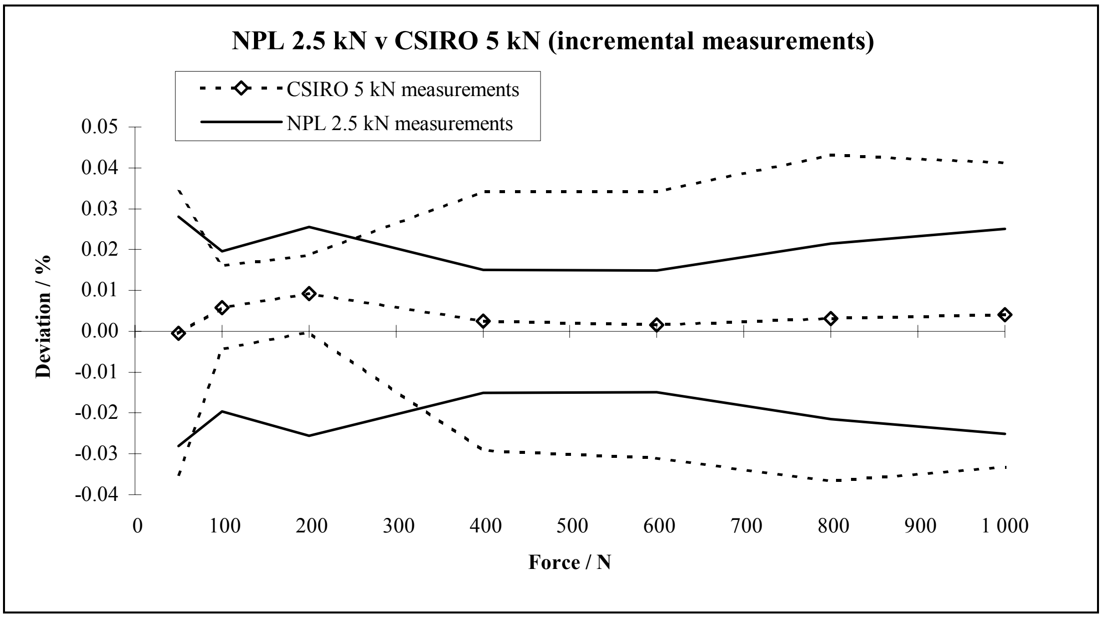


Figure 12: NPL 2.5 kN v CSIRO 5 kN machine for incremental forces

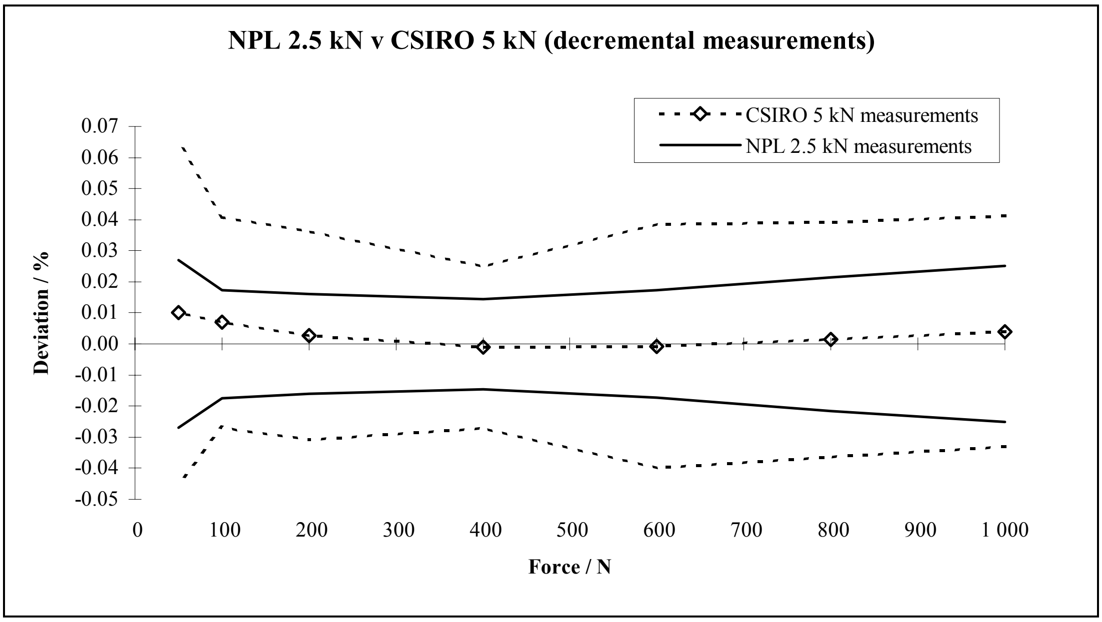


Figure 13: NPL 2.5 kN v CSIRO 5 kN machine for decremental forces

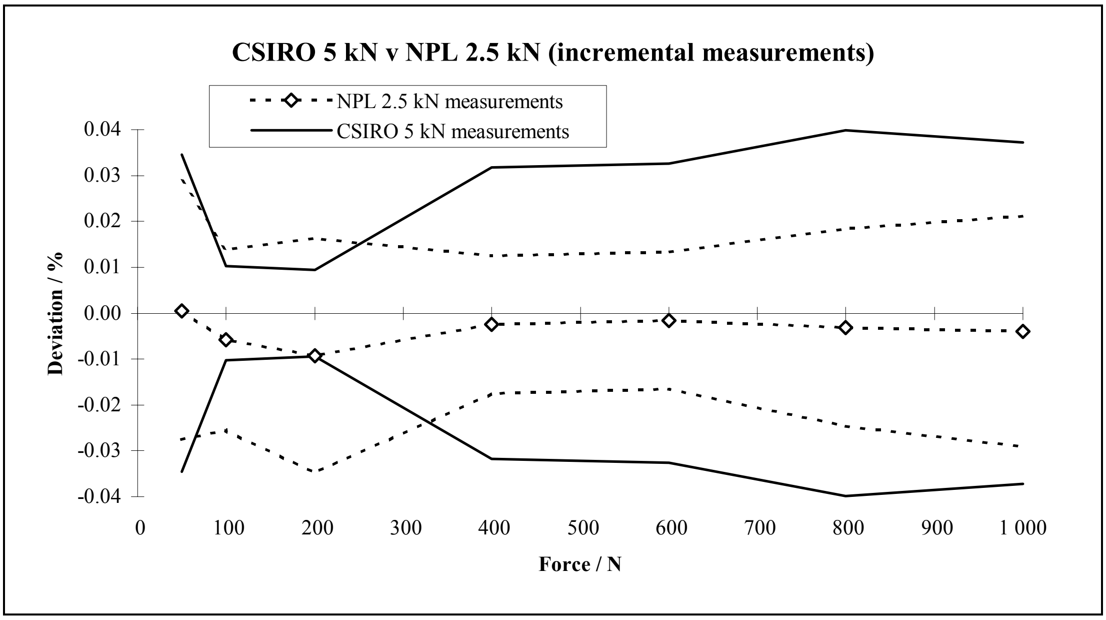


Figure 14: CSIRO 5 kN v NPL 2.5 kN machine for incremental forces

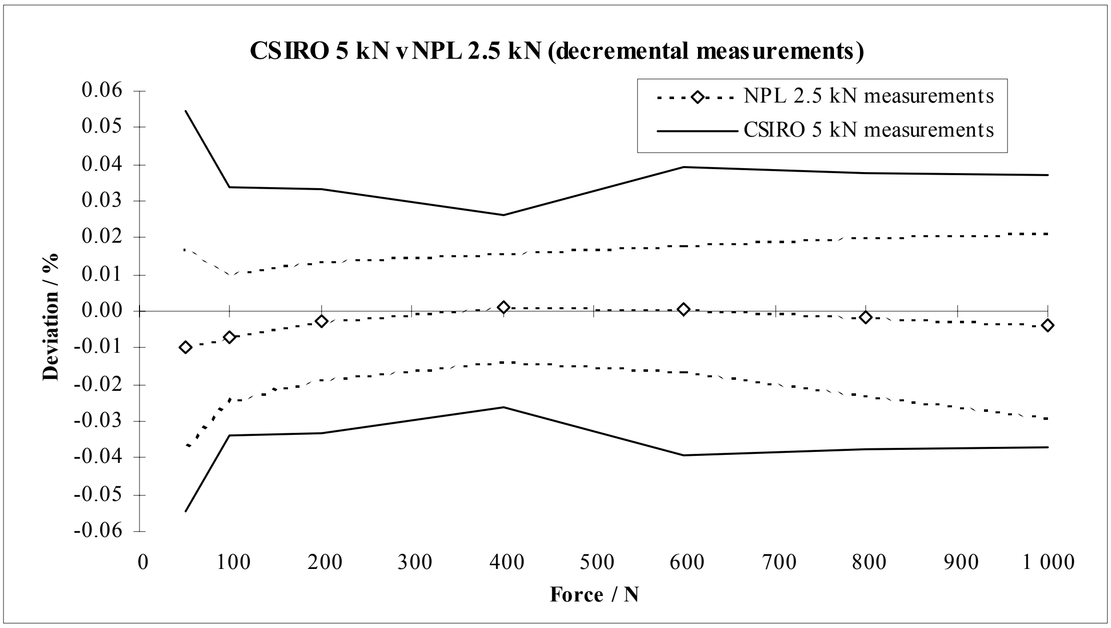


Figure 15: CSIRO 5 kN v NPL 2.5 kN machine for decremental forces

8. Observations

The calibration of the 1 kN load cell required forces of 600, 800, 1 000, 800, and 600 N to be applied in that order. The CSIRO 5 kN deadweight force standard machine was unable to achieve this and an intermediate force of 300 N had to be applied between the 600 - 800 N and 800 - 600 N steps. This may have had an effect on the subsequent readings from the load cell.

The uncertainty in forces measured by a load cell exceed those generated by high accuracy force standard machines. Consequently, when using a load cell as a transfer standard, high accuracy force standard machines may not agree within their stated uncertainties. The uncertainty due to the load cell must be included when comparing measurements.

It is usually recommended that load cells are not used below 40 % of their rated capacity for high-accuracy intercomparison work. Below this level they can be more sensitive to end loading conditions. In this intercomparison the three load cells were used down to either 10 % or 5 % of their rated capacity. This is reflected in the results in the summary below.

A cylindrical measuring spring type load cell was selected to measure the forces between 0.5 kN and 5 kN. As it is hard to find high accuracy cylindrical measuring spring type load cells to measure small forces, particularly below 2.5 kN, two ‘S’ type bending beam load cells were selected to measure the forces between 0.25 kN and 2.5 kN, and between 0.05 kN and 1 kN. The main cause of errors in using this type of load cell is due to the load cell’s sensitivity to side loading, so great care was required in positioning these load cells within the deadweight force standard machines. Locating ball seating units and loading pads were used to minimise the possibility of side forces being introduced during the calibrations.

9. Summary

The results showed that the forces generated by each of the laboratories' deadweight force standard machines agreed between -0.005 % and +0.009 3 % for increasing forces, and between -0.035 8 % and +0.010 % for decreasing forces.

The agreement between the machines when the load cells calibrated range is restricted to between 40 % and 100 % of its maximum capacity is far greater; i.e. between -0.003 8 % and +0.006 6 % for increasing forces, and between -0.009 8 % and +0.007 5 % for decreasing forces.

The agreements were all within the calculated uncertainties of measurement. The differences between the forces measured in the force standard machines are summarised in Tables 2 and 3 below.

Table 2

Range of deviation of measured forces between the deadweight force standard machines

Machine	Stated uncertainty	NPL 20 kN ±0.001 %		NPL 2.5 kN ±0.001 %		NPL 2.5 kN ±0.001 %	
		5 kN load cell		2.5 kN load cell		1 kN load cell	
		Increasing	Decreasing	Increasing	Decreasing	Increasing	Decreasing
CSIRO 5 kN	±0.002 %	-0.003 8 % to -0.000 6%	-0.0006 % to +0.007 5 %	-0.005 0% to +0.006 6%	-0.035 8 % to +0.004 1 %	-0.000 5 % to +0.009 3 %	-0.001 1 % to +0.010 0 %

Table 3

Range of deviation of measured forces between the deadweight force standard machines within the range of 40 % to 100 % of the load cell's capacity

Machine	Stated uncertainty	NPL 20 kN ±0.001 %		NPL 2.5 kN ±0.001 %		NPL 2.5 kN ±0.001 %	
		5 kN load cell		2.5 kN load cell		1 kN load cell	
		Increasing	Decreasing	Increasing	Decreasing	Increasing	Decreasing
CSIRO 5 kN	±0.002 %	-0.003 8 % to -0.000 6%	-0.0006 % to +0.007 5 %	±0.000 0% to +0.006 6%	-0.009 8 % to +0.004 1 %	±0.000 0 % to +0.004 0 %	-0.001 1 % to +0.004 0 %

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11. References

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[3] National Physical Laboratory, “Certificate of Calibration for three masses of the NPL 20 kN machine, Reference: 08C021/9721, 1 December 1998

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[5] National Physical Laboratory, “Certificate of Calibration” for the NPL 2.5 kN machine, Reference: 08F/MCUNC1/6, 17 February 1998

[6] Liam Maybank, Andy Knott, and David Elkington, “Guide to the uncertainty of force measurement”, NPL Report CMAM 24, April 1999