NPL REPORT CMAM 33

# Intercomparison of force standards between NPL, NIM, and SCL

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## Abstract

This report describes the NPL-piloted intercomparison of compressive force measurements between: Standards and Calibration Laboratory (SCL), Kowloon Bay, Hong Kong Special Administrative Region of the People's Republic of China; National Institute of Metrology (NIM), Beijing, People's Republic of China; and National Physical Laboratory (NPL), Teddington, United Kingdom. Forces were measured in the range from 50 kN to 3 MN during the period from 6 January 1999 to 14 March 1999. The results showed that the forces generated by force standard machines of the three laboratories agreed to better than: ±0.05 % for the hydraulic amplification force standard machines, and ±0.006 % for the deadweight force standard machines. The agreements were all within the calculated uncertainties of measurement.

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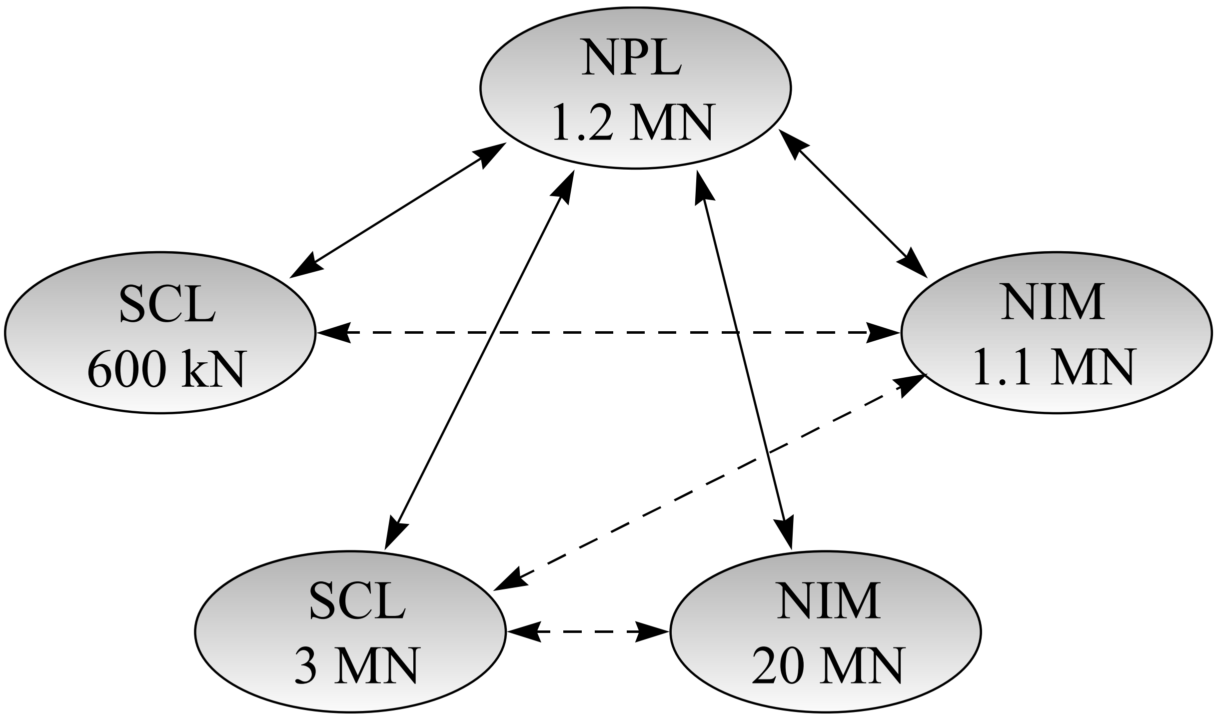
## 1. Introduction

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 in the UK (NPL) and China (NIM). NPL had recently set up and calibrated the force machines in Hong Kong (SCL) who also participated in the intercomparison.

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, SCL, NIM, and NPL. The solid lines therefore represent full intercomparisons with pre and post measurements at NPL. The broken lines indicate intercomparisons calculated from the data obtained from the full intercomparisons.



## 2. Force standard machines

Deadweight force standard machines and hydraulic amplification 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:

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

where $m_c$ is the conventional mass of the weight, $g$ is the local gravitational acceleration, $\rho_a$ is the air density, and $\rho_w$ is the density of the weight.

The forces are traceable to the base SI units of mass, length, and time, and they are therefore termed primary machines. Deadweight machines capable of generating large forces are expensive and there are few in the world with capacities much above 1 MN.

Hydraulic amplification force standard machines amplify the force generated by a deadweight machine. The deadweight machine applies a compression force to a small piston which is hydraulically connected to a larger piston. The force is amplified by the ratio of the area of the larger piston to the area of the smaller one. These machines have only an indirect traceability back to the base SI units and are thus termed secondary machines.

### 2.1 NPL 1.2 MN deadweight force standard machine

The NPL 1.2 MN deadweight force standard machine has a rigid framework on solid foundations providing support for both the device under test and the weights not in use. It has a two-part scalepan and 55 austenitic stainless steel weights. The design of the machine enables a smooth transfer of force to the transducer under test, both incrementally and decrementally.

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

±0.001 % in the range of 1.2 MN down to 10 kN

## 2.2 SCL 600 kN hydraulic amplification force standard machine

The SCL 600 kN hydraulic amplification force standard machine is based on a 60 kN deadweight machine.

The claimed uncertainties of the forces applied by the machine are[4]:

±0.02 % in the range of 600 kN down to 60 kN, Software tare offset 1.
±0.05 % in the range of 600 kN down to 30 kN, Software tare offset 1.
±0.05 % in the range of 600 kN down to 10 kN, Software tare offset 2.

## 2.3 SCL 3 MN hydraulic amplification force standard machine

The SCL 3 MN hydraulic amplification force standard machine is based on a 60 kN deadweight machine.

The claimed uncertainty of the forces applied by the machine is[5]:

±0.05 % in the range of 3 MN down to 50 kN, Software tare offset 0.73 N.

## 2.4 NIM (Lab 102) 1.1 MN deadweight force standard machine

The NIM 1.1 MN deadweight force standard machine has a rigid framework on solid foundations providing support for both the device under test and the masses not in use. It has a scalepan and a set of austenitic stainless steel weights. The design of the machine enables a smooth transfer of force to the transducer under test, both incrementally and decrementally.

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

±0.002 % in the range of 1.1 MN down to 20 kN

## 2.5 NIM 20 MN hydraulic amplification force standard machine

The NIM 20 MN force standard machine is based on a 40 kN deadweight machine.

The claimed uncertainties of the forces applied by the machine are:

±0.01 % in the range of 20 MN down to 0.5 MN in compression
±0.01 % in the range of 10 MN down to 0.5 MN in tension

## 2.6 Intercomparison equipment

Three NPL-designed and built strain gauge load cells (serial numbers 1200/1C, 1200/2C, and 1200/3C), and one Revere Transducers load cell (serial number 240503-97) were used in the intercomparison.

All four load cells have a cylindrical steel element with eight strain gauges bonded to the surface. The strain gauge bridges are temperature compensated. The three NPL load cells each have a locating ball seating unit. The Revere Transducers load cell has a domed upper loading face. The outputs from the three NPL load cells are taken to a switch box where they are summed. The output from the switch box or the Revere Transducers load cell is measured by a precision AC ratio meter (HBM DMP 39 serial number 102).

# 3. Test procedure

## 3.1 Positioning of the load cells in the force standard machines

At NPL, the three 1.2 MN load cells were calibrated in series. The load cells were located on top of each other in the following order: 1200/3C at the bottom, 1200/2C in the middle, and 1200/1C on top with its associated ball seating unit. Experiment at NPL has shown that this is a valid method of calibration[7].

At SCL and NIM, the three 1.2 MN load cells were loaded in parallel. The load cells, with their individual ball seating units, were placed in a triangular formation on a flat loading pad. 1200/1C was positioned at the front, 1200/2C at the back left, and 1200/3C at the back right. A spherical seating was then placed centrally on top of a pad centred on the three individual ball seating units.

The three 1.2 MN load cells were centred in each machine so that the outputs from each load cell were balanced to within 0.1 mV/V to ensure that the force was applied uniaxially through the load cell arrangement.

The Revere 1 MN load cell was placed centrally on a flat loading pad with a soft loading pad placed centrally on the load cell's domed upper loading face.

All the measurements were made following a timed loading sequence to minimise the effects of creep.

The timed loading sequence is illustrated in figure 1. Following a change of applied force, no readings are taken for a period of two minutes.

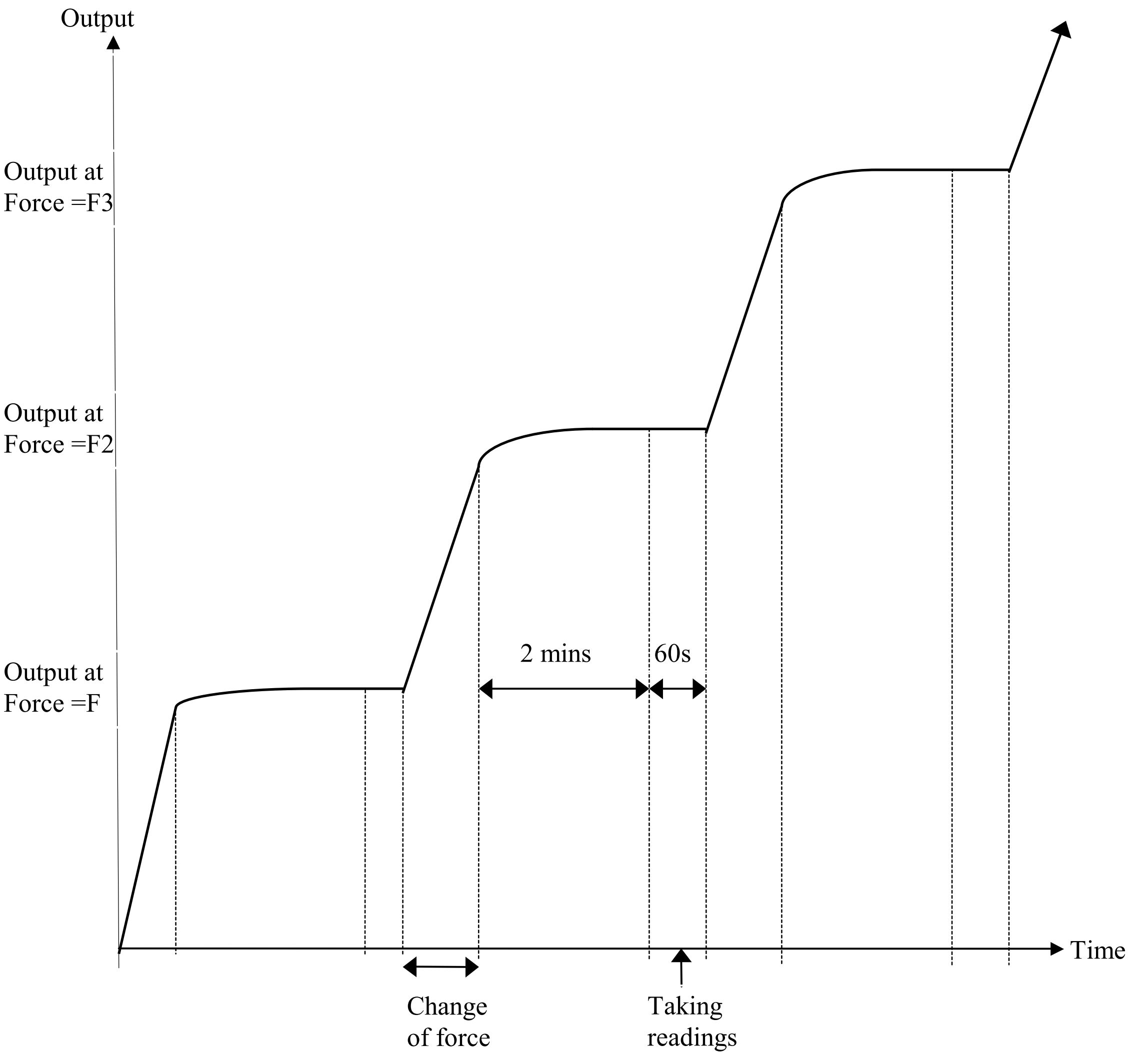



Figure 1: Timed loading sequence

Each measurement series was made up of seven runs. After the first two runs, each load cell was rotated through 120° (when using the three NPL load cells, they were rotated individually but their position in the machines was not altered). 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.

## 4. Results obtained in the NPL 1.2 MN deadweight force standard machine

Sections 4.1 and 4.2 contain a summary of the measurements made at NPL both before (pre) and after (post) the visits to Hong Kong and Beijing. 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 rotations. 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 1.2 MN 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 1.2 MN deadweight force standard machine.

## 4.1 1 MN load cell calibrated in NPL's 1.2 MN deadweight force standard machine

| nominal force | pre | | post | | | overall mean | |
|---|---|---|---|---|---|---|---|
| | mean output | uncertainty | mean output | uncertainty | drift | output | uncertainty |
| kN | mV/V | % | mV/V | % | % | mV/V | % |
| 50 | 0.101 961 | 0.011 | 0.101 984 | 0.007 | 0.013 | 0.101 973 | 0.028 |
| 120 | 0.245 003 | 0.005 | 0.245 037 | 0.004 | 0.008 | 0.245 020 | 0.017 |
| 180 | 0.367 650 | 0.003 | 0.367 693 | 0.003 | 0.007 | 0.367 671 | 0.014 |
| 240 | 0.490 302 | 0.002 | 0.490 356 | 0.003 | 0.006 | 0.490 329 | 0.013 |
| 360 | 0.735 622 | 0.002 | 0.735 692 | 0.003 | 0.006 | 0.735 657 | 0.011 |
| 480 | 0.980 958 | 0.001 | 0.981 039 | 0.003 | 0.005 | 0.980 998 | 0.010 |
| 600 | 1.226 291 | 0.001 | 1.226 390 | 0.003 | 0.005 | 1.226 341 | 0.010 |
| 480 | 0.980 996 | 0.001 | 0.981 085 | 0.003 | 0.005 | 0.981 041 | 0.011 |
| 360 | 0.735 690 | 0.001 | 0.735 763 | 0.003 | 0.006 | 0.735 726 | 0.012 |
| 240 | 0.490 379 | 0.002 | 0.490 437 | 0.002 | 0.007 | 0.490 408 | 0.014 |
| 180 | 0.367 717 | 0.003 | 0.367 771 | 0.002 | 0.009 | 0.367 744 | 0.017 |
| 120 | 0.245 056 | 0.003 | 0.245 098 | 0.002 | 0.010 | 0.245 077 | 0.020 |
| 50 | 0.101 990 | 0.004 | 0.102 007 | 0.005 | 0.010 | 0.101 999 | 0.020 |

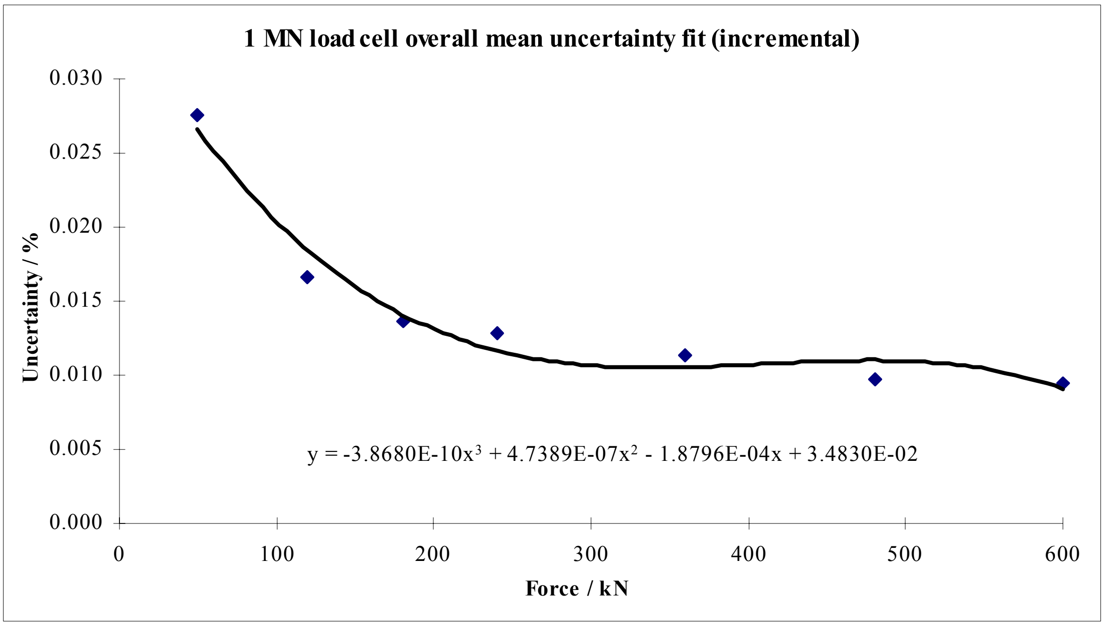



Figure 2: 1 MN load cell overall mean uncertainty fit for incremental forces

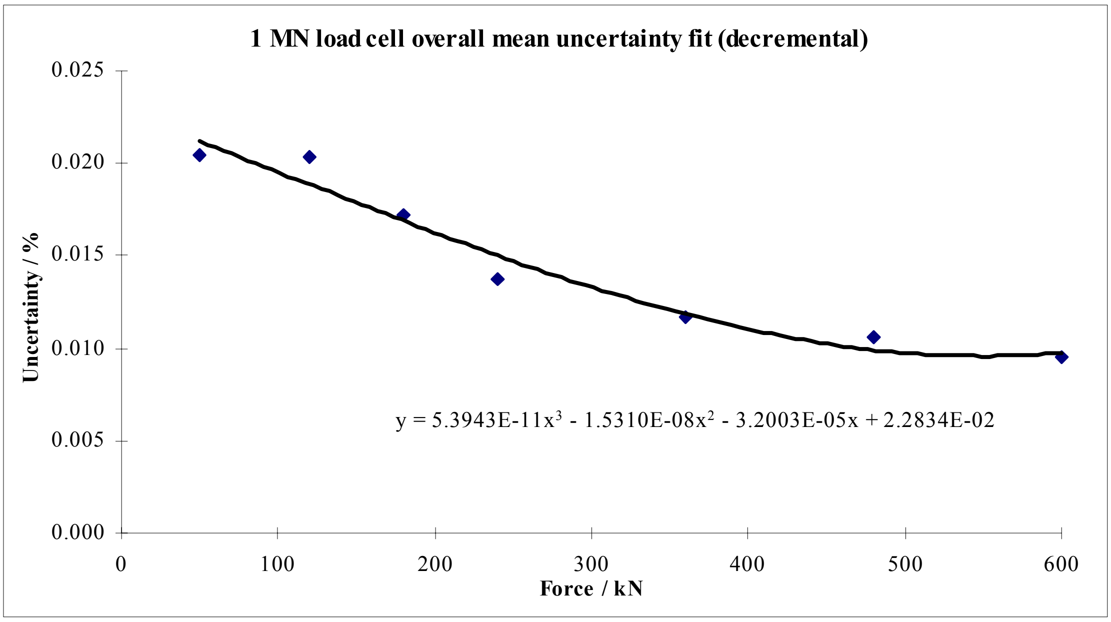



Figure 3: 1 MN load cell overall mean uncertainty fit for decremental forces

## 4.2 Three 1.2 MN load cells calibrated in series in NPL's 1.2 MN deadweight force standard machine

| applied force kN | effective force kN | pre mean output mV/V | pre uncertainty % | post mean output mV/V | post uncertainty % | drift % | overall mean output mV/V | overall mean uncertainty % |
|---|---|---|---|---|---|---|---|---|
| 200 | 600 | 0.361 380 | 0.003 | 0.361 383 | 0.006 | 0.000 | 0.361 381 | 0.005 |
| 300 | 900 | 0.541 866 | 0.005 | 0.541 867 | 0.006 | 0.000 | 0.541 866 | 0.005 |
| 400 | 1 200 | 0.722 213 | 0.006 | 0.722 210 | 0.006 | 0.000 | 0.722 211 | 0.006 |
| 500 | 1 500 | 0.902 435 | 0.008 | 0.902 424 | 0.007 | -0.001 | 0.902 430 | 0.007 |
| 600 | 1 800 | 1.082 514 | 0.010 | 1.082 502 | 0.007 | -0.001 | 1.082 508 | 0.008 |
| 700 | 2 100 | 1.262 446 | 0.017 | 1.262 461 | 0.012 | 0.001 | 1.262 454 | 0.014 |
| 800 | 2 400 | 1.442 231 | 0.018 | 1.442 236 | 0.016 | 0.000 | 1.442 233 | 0.017 |
| 900 | 2 700 | 1.621 872 | 0.022 | 1.621 872 | 0.018 | 0.000 | 1.621 872 | 0.020 |
| 1 000 | 3 000 | 1.801 359 | 0.023 | 1.801 361 | 0.019 | 0.000 | 1.801 360 | 0.021 |
| 900 | 2 700 | 1.621 895 | 0.022 | 1.621 903 | 0.018 | 0.000 | 1.621 899 | 0.020 |
| 800 | 2 400 | 1.442 303 | 0.023 | 1.442 305 | 0.019 | 0.000 | 1.442 304 | 0.021 |
| 700 | 2 100 | 1.262 577 | 0.021 | 1.262 576 | 0.017 | 0.000 | 1.262 577 | 0.019 |
| 600 | 1 800 | 1.082 700 | 0.024 | 1.082 697 | 0.018 | 0.000 | 1.082 699 | 0.021 |
| 500 | 1 500 | 0.902 668 | 0.018 | 0.902 660 | 0.014 | 0.000 | 0.902 664 | 0.016 |
| 400 | 1 200 | 0.722 482 | 0.012 | 0.722 462 | 0.009 | -0.002 | 0.722 472 | 0.011 |
| 300 | 900 | 0.542 128 | 0.009 | 0.542 099 | 0.005 | -0.003 | 0.542 114 | 0.009 |
| 200 | 600 | 0.361 592 | 0.006 | 0.361 570 | 0.004 | -0.004 | 0.361 581 | 0.009 |

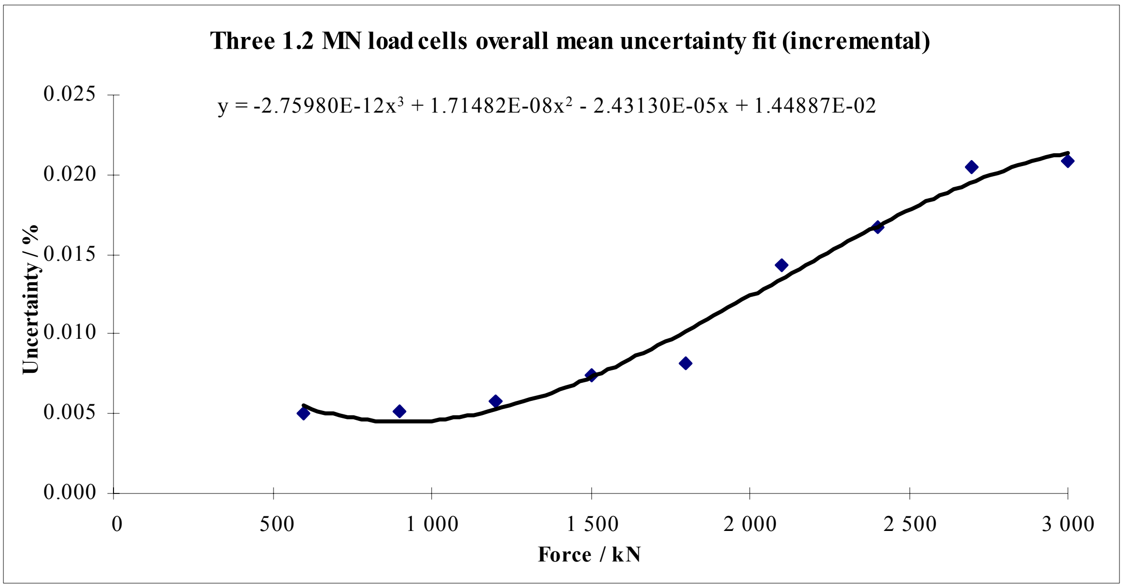



Figure 4: Three 1.2 MN load cells overall mean uncertainty fit for incremental forces

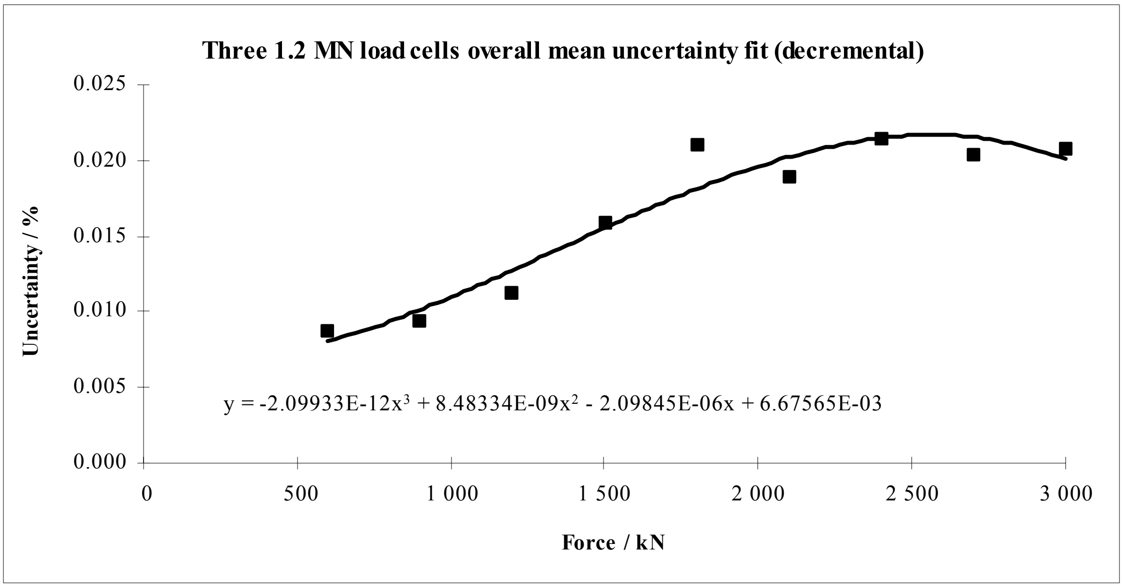



Figure 5: Three 1.2 MN load cells overall mean uncertainty fit for decremental forces

## 5. Calculation of non-matching data points

Where the nominal force values used are not the same in both machines a least squares polynomial fit has been used to calculate the value of deviation or uncertainty for one machine at the nominal forces used in the other. The order of polynomial was chosen to give the most suitable fit. The most suitable fit is not necessarily the one with the lowest errors. For example, a 4th order fit will always pass through any five points exactly but does not necessarily represent the true characteristics of the data. This is illustrated in figure 6.

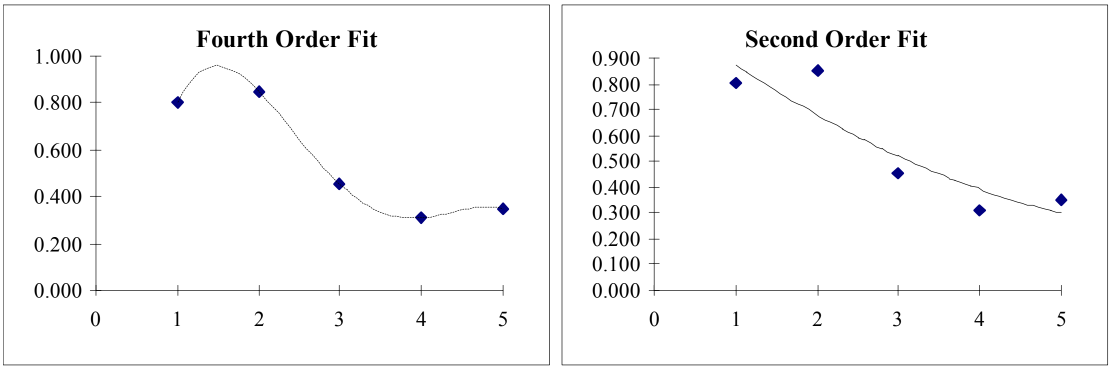



Figure 6: Illustration of polynomial fitting of data.

## 6. Results of intercomparison between NPL and SCL

The comparison between NPL and SCL cannot be treated as a true intercomparison, as the SCL hydraulic machines are currently traceable to NPL. The machines were set up and adjusted so that the forces generated by these machines were within set tolerances of the forces generated by the NPL machines.

The SCL machines are designed to apply different forces to those used to calibrate the load cells at NPL. A 5$^{th}$ order polynomial was fitted to the measurement results so that a comparison could be made between NPL, SCL, and NIM.

Sections 6.1 and 6.3 contain a summary of the measurements made at SCL. 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:

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

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

The machines 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 that of the measured deviation.

## 6.1 SCL 600 kN hydraulic amplification machine

### 6.1.1 Results using the 1 MN load cell

| 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 |
|---|---|---|---|---|---|---|---|---|
| 50 | 0.101 967 | 50.000 | 0.000 | 0.000 | 0.027 | -0.027 | 0.027 | YES |
| 120 | 0.245 010 | 119.999 | -0.001 | -0.001 | 0.021 | -0.022 | 0.020 | YES |
| 180 | 0.367 656 | 179.993 | -0.007 | -0.004 | 0.015 | -0.018 | 0.011 | YES |
| 240 | 0.490 296 | 239.989 | -0.011 | -0.005 | 0.014 | -0.019 | 0.010 | YES |
| 360 | 0.735 597 | 359.973 | -0.027 | -0.008 | 0.012 | -0.019 | 0.004 | YES |
| 480 | 0.980 897 | 479.954 | -0.046 | -0.010 | 0.010 | -0.020 | 0.001 | YES |
| 600 | 1.226 151 | 599.910 | -0.090 | -0.015 | 0.010 | -0.025 | -0.005 | YES |
| 480 | 0.980 939 | 479.953 | -0.047 | -0.010 | 0.011 | -0.021 | 0.001 | YES |
| 360 | 0.735 692 | 359.985 | -0.015 | -0.004 | 0.014 | -0.018 | 0.010 | YES |
| 240 | 0.490 402 | 240.002 | 0.002 | 0.001 | 0.015 | -0.014 | 0.016 | YES |
| 180 | 0.367 745 | 180.001 | 0.001 | 0.001 | 0.019 | -0.018 | 0.020 | YES |
| 120 | 0.245 080 | 120.005 | 0.005 | 0.004 | 0.022 | -0.017 | 0.026 | YES |
| 50 | 0.101 991 | 49.999 | -0.001 | -0.001 | 0.023 | -0.024 | 0.022 | YES |

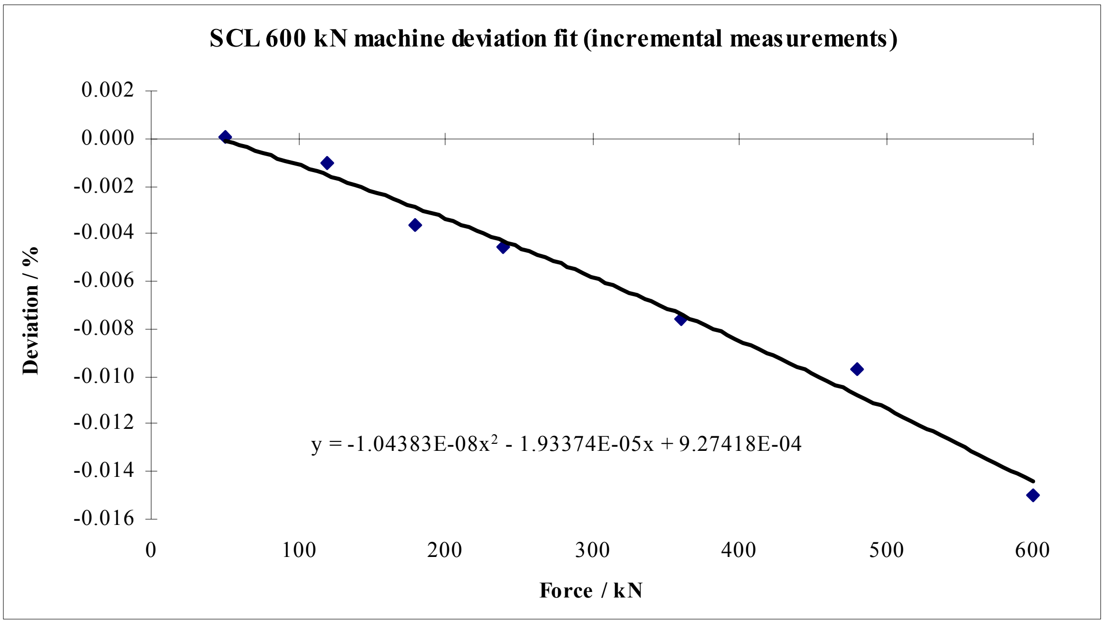



Figure 7: SCL 600 kN machine deviation fit for incremental forces

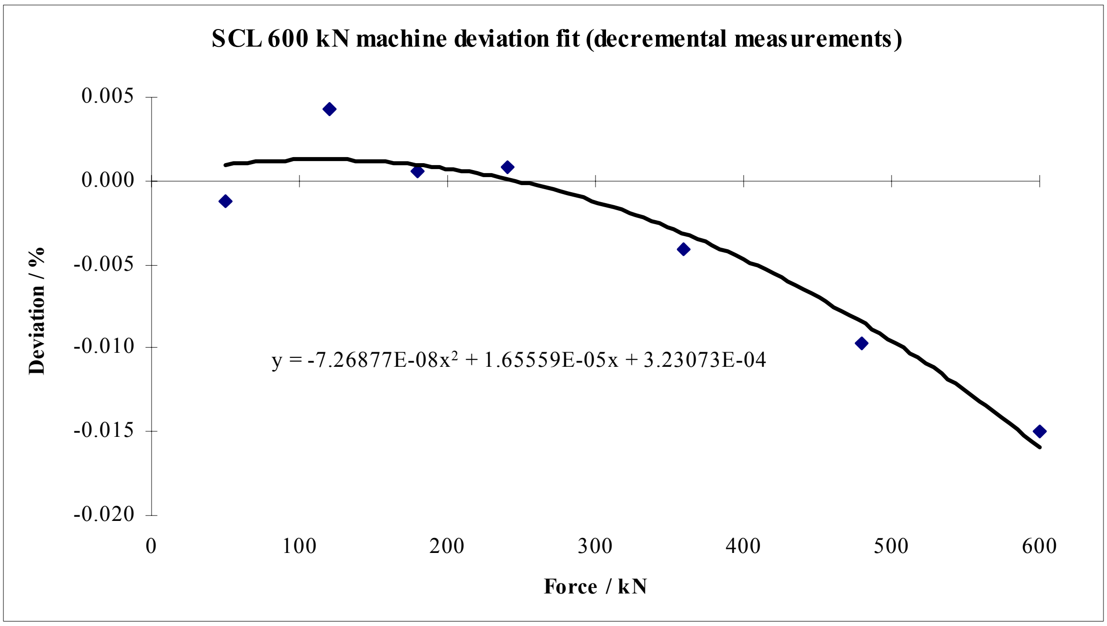



Figure 8: SCL 600 kN machine deviation fit for decremental forces

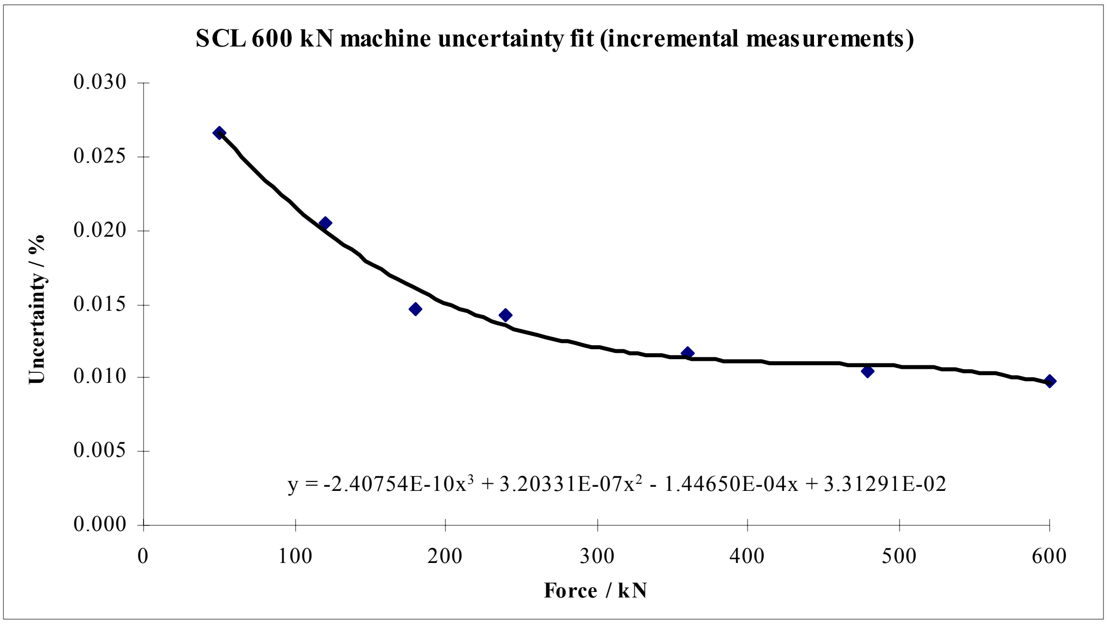



Figure 9: SCL 600 kN machine uncertainty fit for incremental forces

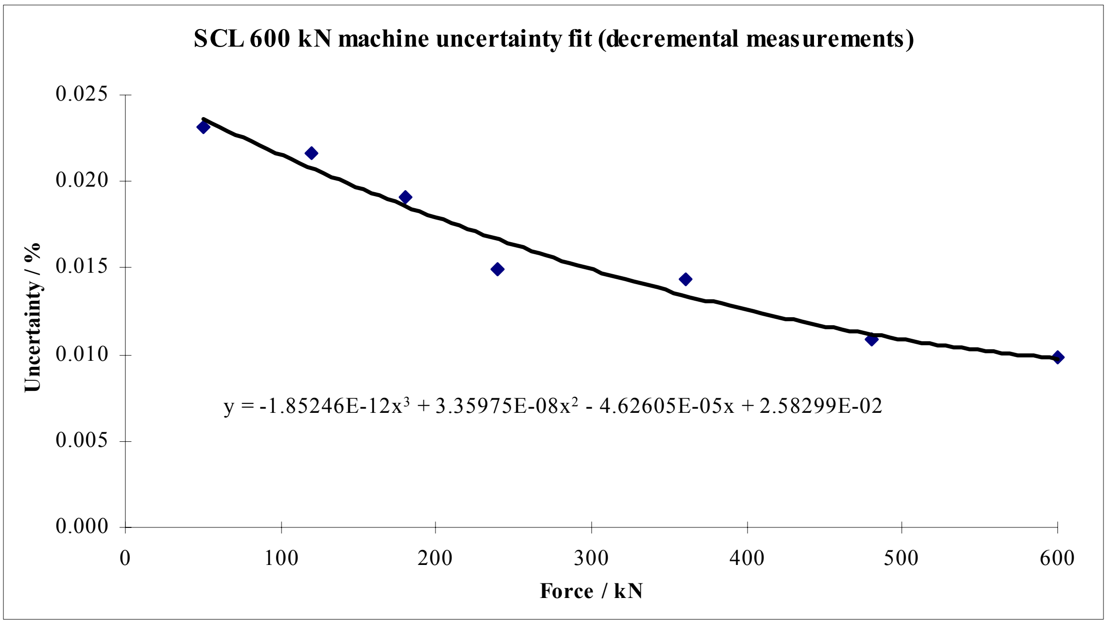



Figure 10: SCL 600 kN machine uncertainty fit for decremental forces

## 6.2 Comparison of results between the NPL 1.2 MN machine and the SCL 600 kN machine

The results from this intercomparison differ from those in the calibration certificate for the SCL 600 kN machine[4] because the calibration of the machine utilised only the NPL pre data and the intercomparison of the machine utilised both the NPL pre and NPL post data. The uncertainty calculations include a component due to the load cell which is not included in the certification for the machine.

### 6.2.1 Results using the 1 MN load cell

The following graphs compare the forces measured in the force standard machines. The overall uncertainty of forces measured by the 1 MN load cell was calculated from the measurements made in the NPL 1.2 MN force standard machine (see section 4.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the SCL 600 kN force standard machine from those measured in the NPL 1.2 MN force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the SCL 600 kN force standard machine calculated using the equation on page 11.

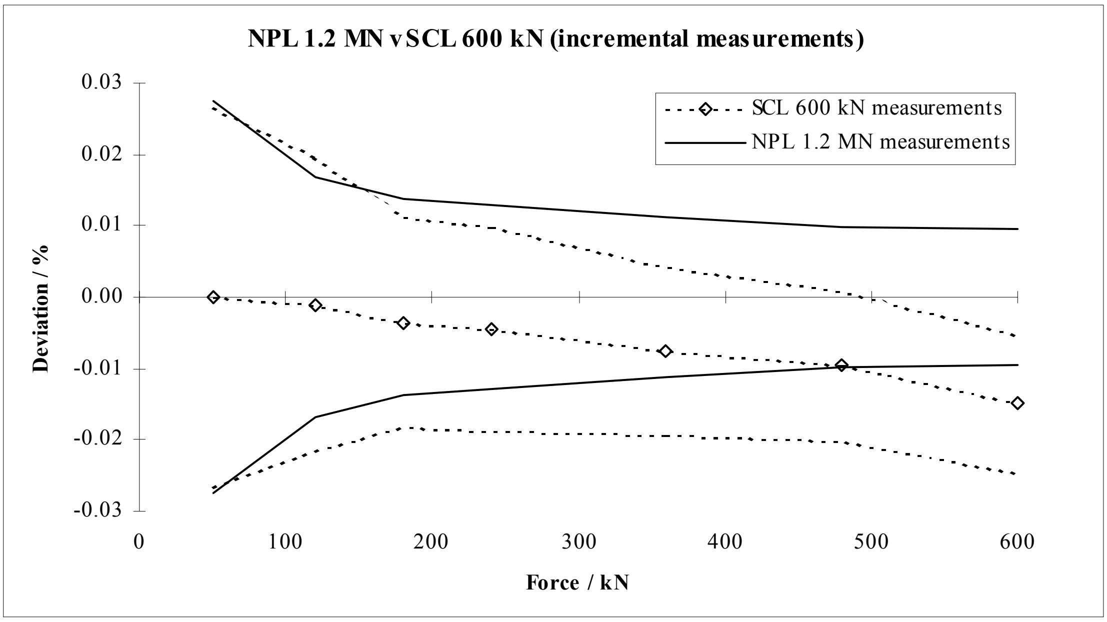



Figure 11: NPL 1.2 MN v SCL 600 kN machine for incremental forces

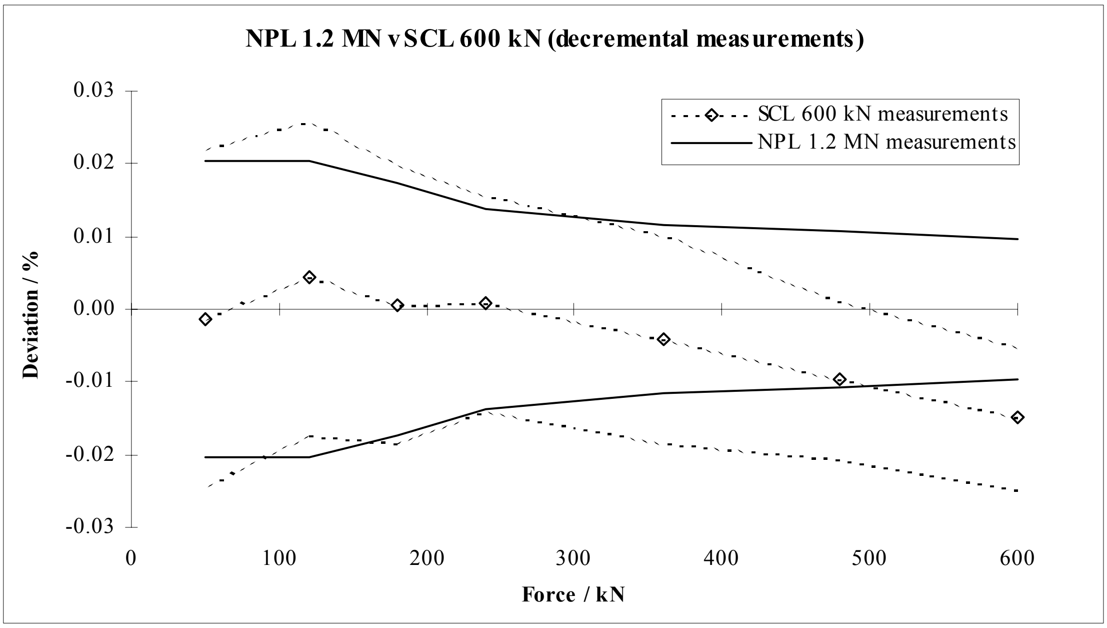



Figure 12: NPL 1.2 MN v SCL 600 kN machine for decremental forces

## 6.3 SCL 3 MN hydraulic amplification machine

The nominal forces generated by the SCL 3 MN force standard machine differ from those generated by the NPL 1.2 MN force standard machine. So that the measurements made at NPL, SCL, and NIM could be compared, 5$^{th}$ order polynomials were fitted to the measured load cell outputs.

### 6.3.1 Results using the 1 MN load cell

| 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 |
|---|---|---|---|---|---|---|---|---|
| 50 | 0.101 998 | 49.999 | -0.001 | -0.002 | 0.030 | -0.032 | 0.028 | YES |
| 100 | 0.204 180 | 100.008 | 0.008 | 0.008 | 0.021 | -0.013 | 0.030 | YES |
| 200 | 0.408 647 | 200.030 | 0.030 | 0.015 | 0.017 | -0.002 | 0.032 | YES |
| 250 | 0.510 849 | 250.027 | 0.027 | 0.011 | 0.017 | -0.006 | 0.027 | YES |
| 350 | 0.715 316 | 350.038 | 0.038 | 0.011 | 0.014 | -0.003 | 0.025 | YES |
| 500 | 1.022 043 | 500.069 | 0.069 | 0.014 | 0.013 | 0.001 | 0.027 | YES |
| 600 | 1.226 509 | 600.069 | 0.069 | 0.011 | 0.012 | 0.000 | 0.023 | YES |
| 500 | 1.022 024 | 500.042 | 0.042 | 0.008 | 0.013 | -0.005 | 0.021 | YES |
| 350 | 0.715 362 | 350.025 | 0.025 | 0.007 | 0.013 | -0.006 | 0.021 | YES |
| 250 | 0.510 897 | 250.011 | 0.011 | 0.005 | 0.015 | -0.010 | 0.019 | YES |
| 200 | 0.408 659 | 199.998 | -0.002 | -0.001 | 0.015 | -0.016 | 0.014 | YES |
| 100 | 0.204 209 | 99.998 | -0.002 | -0.002 | 0.022 | -0.024 | 0.020 | YES |
| 50 | 0.102 002 | 49.988 | -0.012 | -0.023 | 0.029 | -0.053 | 0.006 | YES |

Figures 13 and 14 show the polynomial equation used to give the actual force measured from the mean measured output voltage ratios, where different nominal forces were applied in the two standards laboratories.

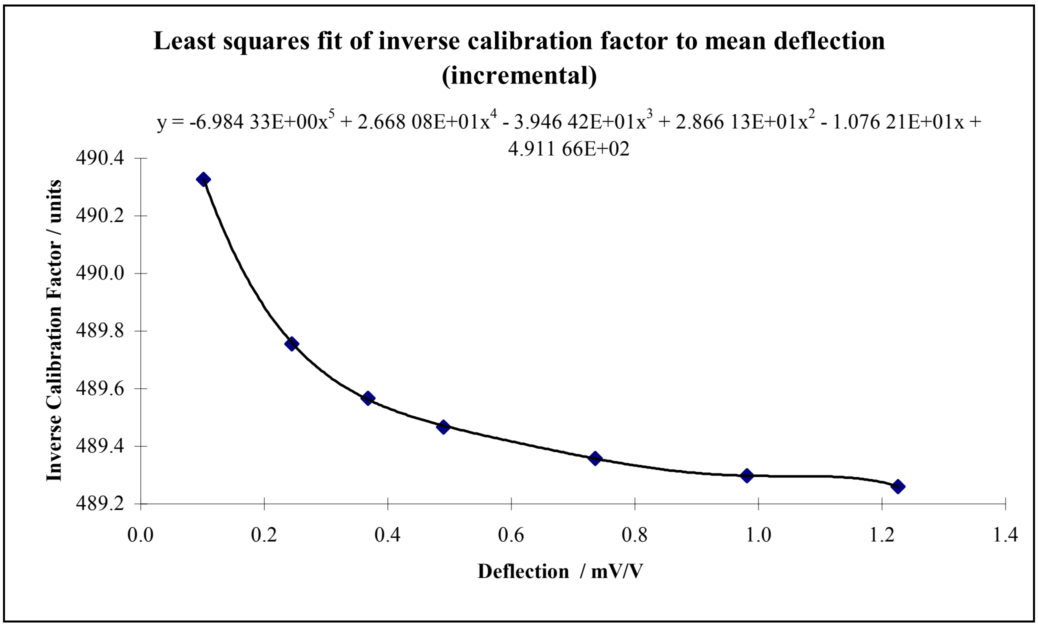



Figure 13: Least squares fit of inverse calibration factor to mean deflection for incremental forces

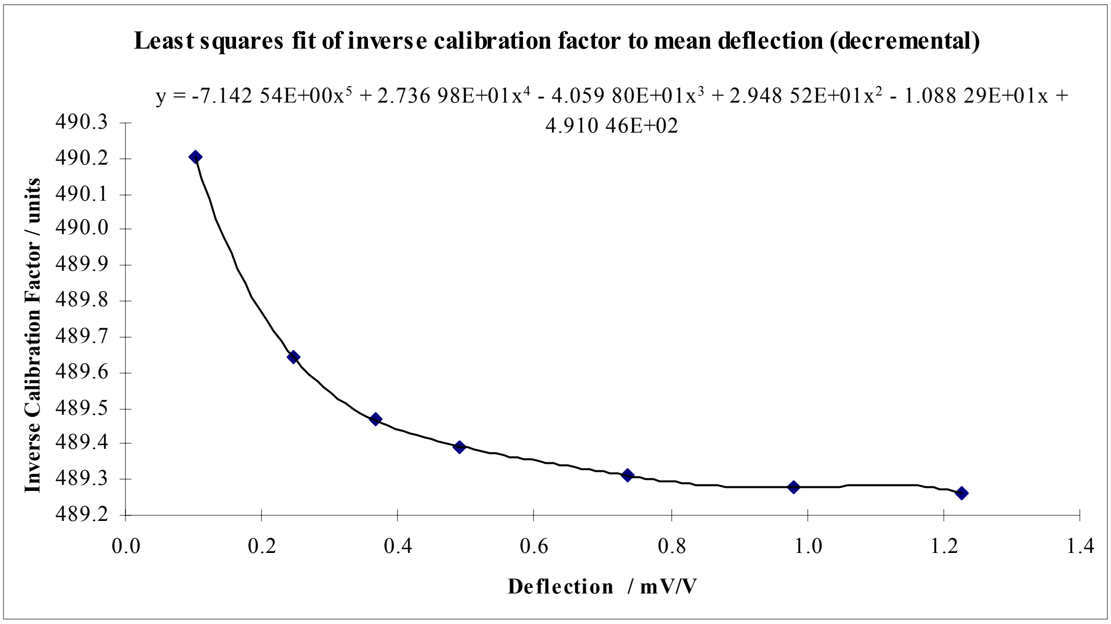



Figure 14: Least squares fit of inverse calibration factor to mean deflection for decremental forces

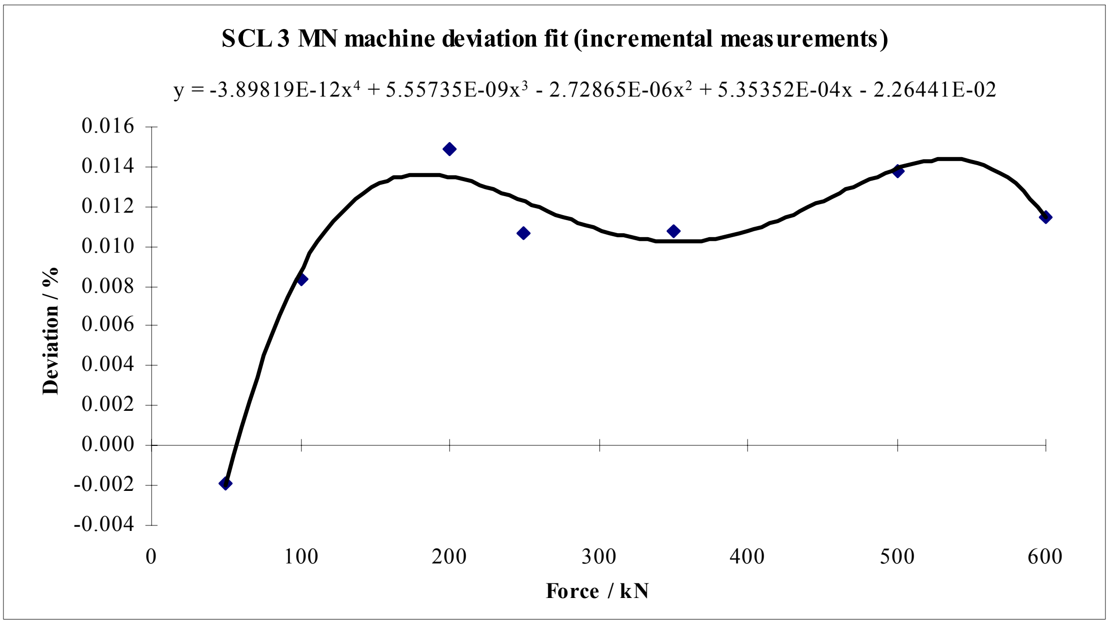



Figure 15: SCL 3 MN machine deviation fit for incremental forces

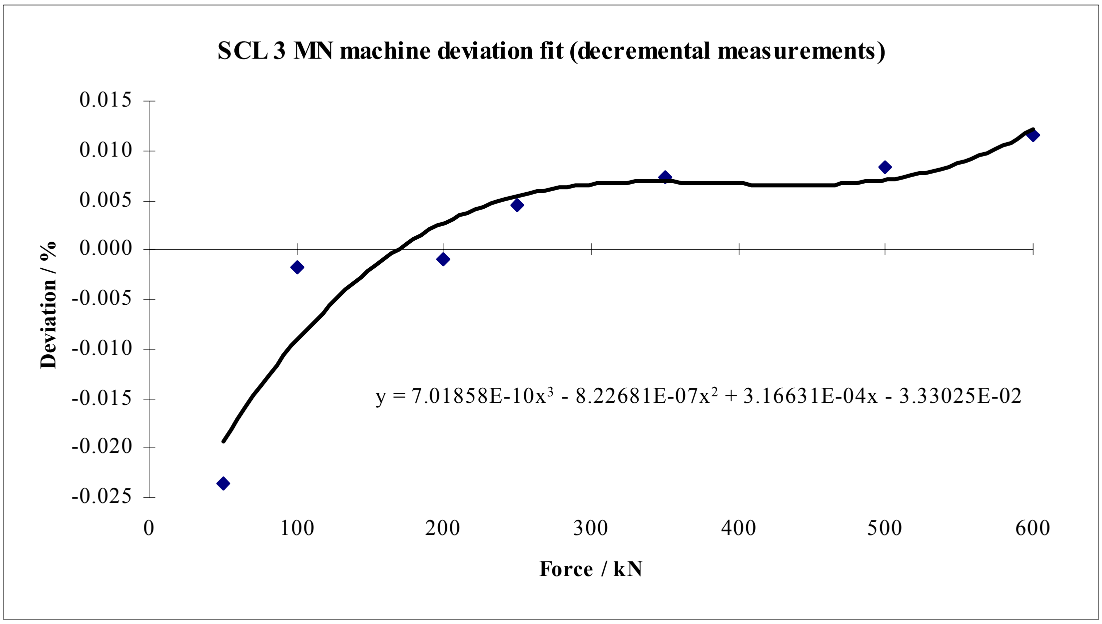



Figure 16: SCL 3 MN machine deviation fit for decremental forces

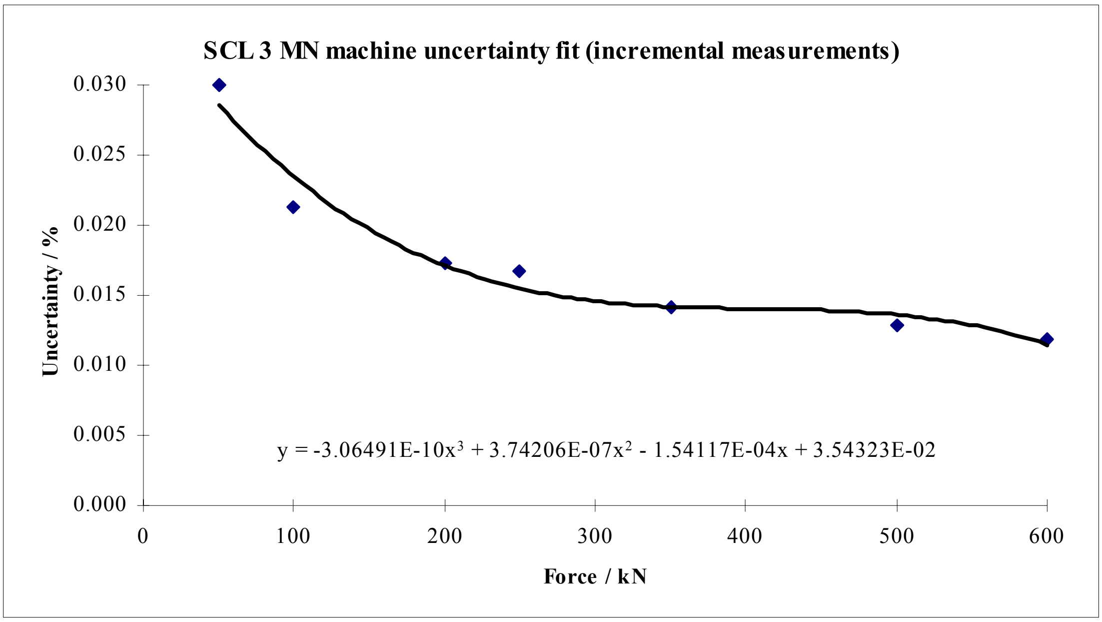



Figure 17: SCL 3 MN machine uncertainty fit for incremental forces

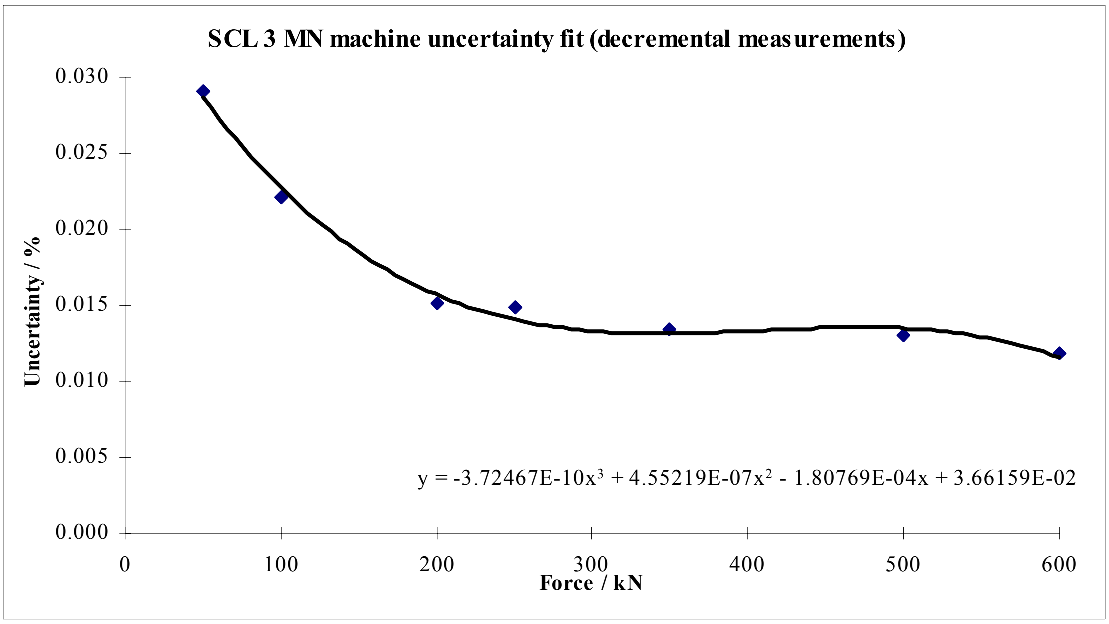



Figure 18: SCL 3 MN machine uncertainty fit for decremental forces

### 6.3.2 Results using three 1.2 MN load cells

| 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 |
|---|---|---|---|---|---|---|---|---|
| 600 | 0.361 454 | 600.107 | 0.107 | 0.018 | 0.012 | 0.006 | 0.030 | YES |
| 900 | 0.541 965 | 900.151 | 0.151 | 0.017 | 0.006 | 0.010 | 0.023 | YES |
| 1 200 | 0.722 336 | 1 200.192 | 0.192 | 0.016 | 0.005 | 0.011 | 0.021 | YES |
| 1 500 | 0.902 564 | 1 500.214 | 0.214 | 0.014 | 0.006 | 0.008 | 0.020 | YES |
| 1 800 | 1.082 637 | 1 800.199 | 0.199 | 0.011 | 0.006 | 0.005 | 0.017 | YES |
| 2 100 | 1.262 562 | 2 100.172 | 0.172 | 0.008 | 0.007 | 0.001 | 0.016 | YES |
| 2 400 | 1.442 305 | 2 400.097 | 0.097 | 0.004 | 0.007 | -0.003 | 0.011 | YES |
| 2 700 | 1.621 979 | 2 700.171 | 0.171 | 0.006 | 0.009 | -0.003 | 0.015 | YES |
| 3 000 | 1.801 501 | 3 000.221 | 0.221 | 0.007 | 0.015 | -0.008 | 0.022 | YES |
| 2 700 | 1.622 161 | 2 700.428 | 0.428 | 0.016 | 0.009 | 0.007 | 0.024 | YES |
| 2 400 | 1.442 590 | 2 400.460 | 0.460 | 0.019 | 0.008 | 0.011 | 0.027 | YES |
| 2 100 | 1.262 789 | 2 100.342 | 0.342 | 0.016 | 0.006 | 0.010 | 0.023 | YES |
| 1 800 | 1.082 897 | 1 800.319 | 0.319 | 0.018 | 0.006 | 0.012 | 0.023 | YES |
| 1 500 | 0.902 821 | 1 500.246 | 0.246 | 0.016 | 0.005 | 0.011 | 0.022 | YES |
| 1 200 | 0.722 600 | 1 200.199 | 0.199 | 0.017 | 0.006 | 0.011 | 0.022 | YES |
| 900 | 0.542 204 | 900.137 | 0.137 | 0.015 | 0.006 | 0.009 | 0.021 | YES |
| 600 | 0.361 640 | 600.085 | 0.085 | 0.014 | 0.006 | 0.008 | 0.020 | YES |

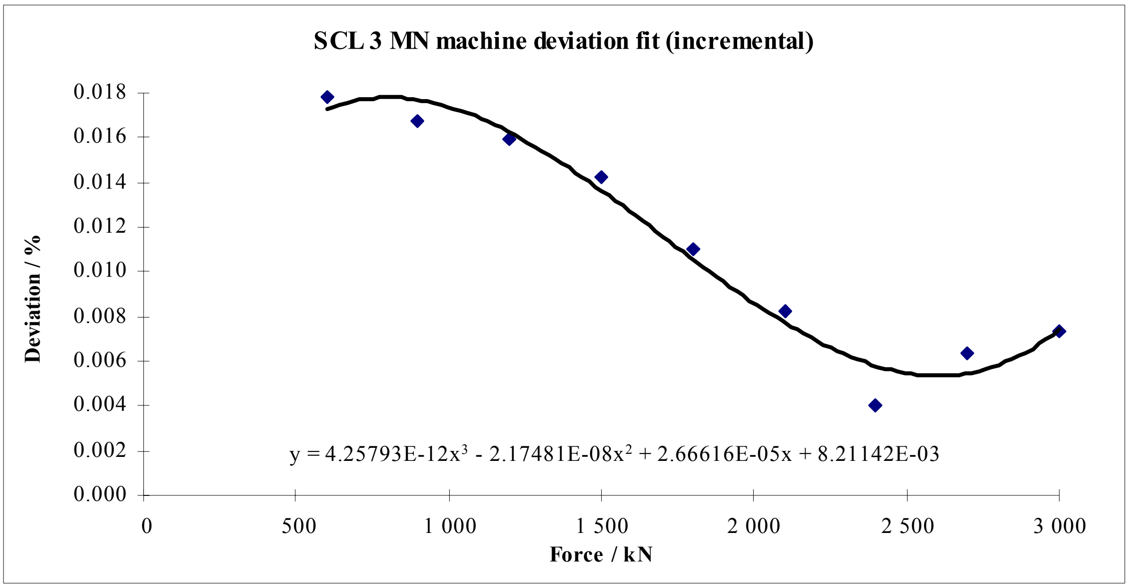



Figure 19: SCL 3 MN machine deviation fit for incremental forces

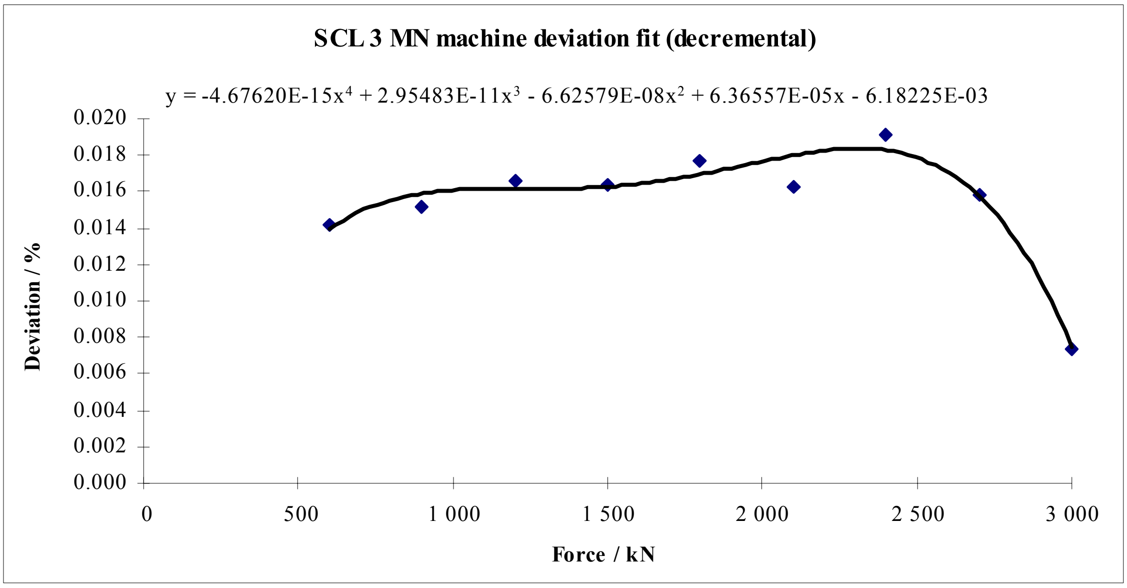



Figure 20: SCL 3 MN machine deviation fit for decremental forces

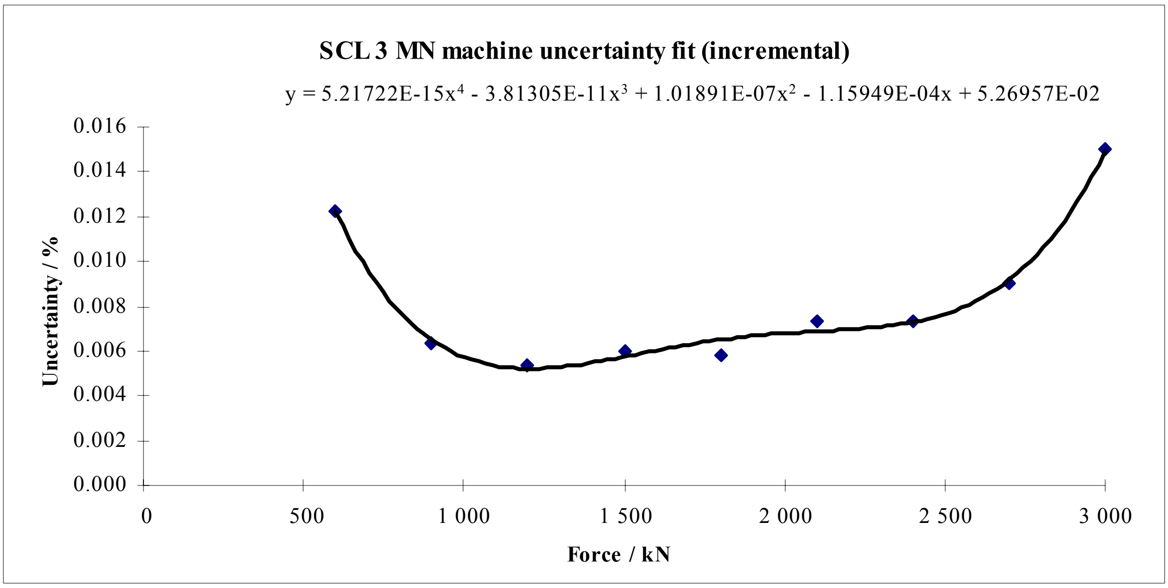



Figure 21: SCL 3 MN machine uncertainty fit for incremental forces

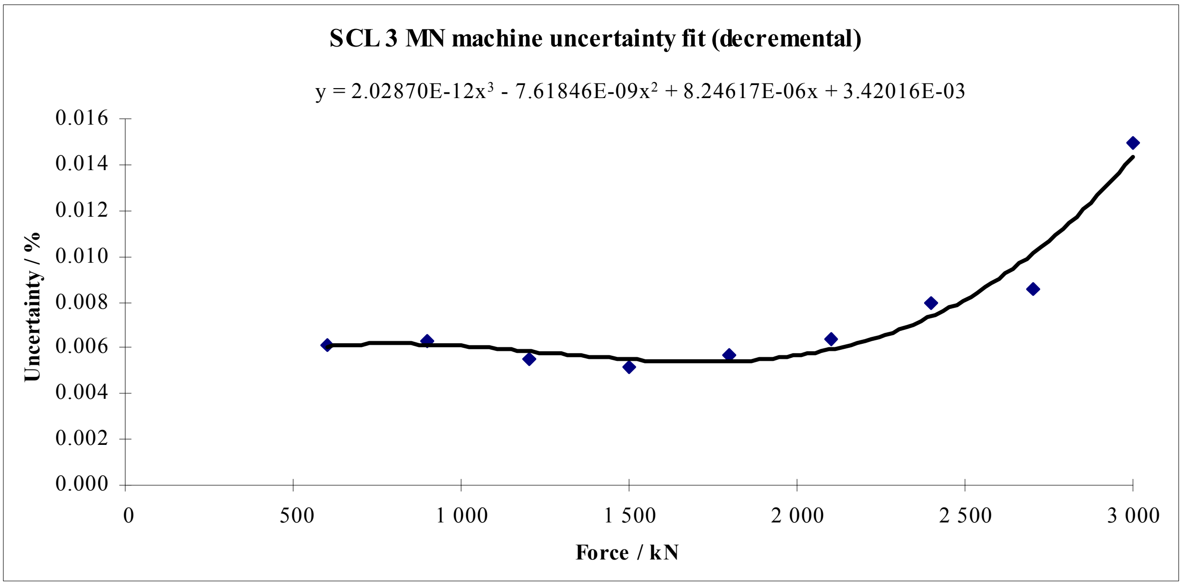



Figure 22: SCL 3 MN machine uncertainty fit for decremental forces

## 6.4 Comparison of results between the NPL 1.2 MN machine and the SCL 3 MN machine

The results from this intercomparison differ from those in the calibration certificate for the SCL 3 MN machine[5] because the calibration of the machine utilised only the NPL pre data and the intercomparison of the machine utilised both the NPL pre and NPL post data. The uncertainty calculations include a component due to the load cell which is not included in the certification for the machine.

### 6.4.1 Results using the 1 MN load cell

The following graphs compare the forces measured in the force standard machines. The overall uncertainty of forces measured by the 1 MN load cell was calculated from the measurements made in the NPL 1.2 MN force standard machine (see section 4.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the SCL 3 MN force standard machine from those measured in the NPL 1.2 MN force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the SCL 3 MN force standard machine calculated using the equation on page 11.

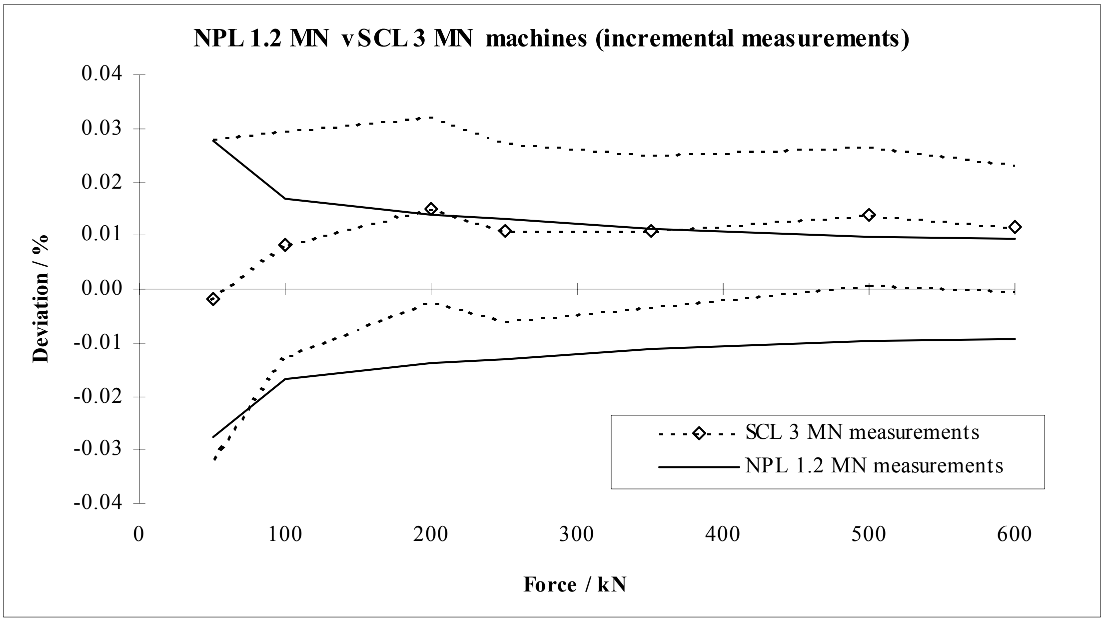



Figure 23: NPL 1.2 MN v SCL 3 MN machine for incremental forces

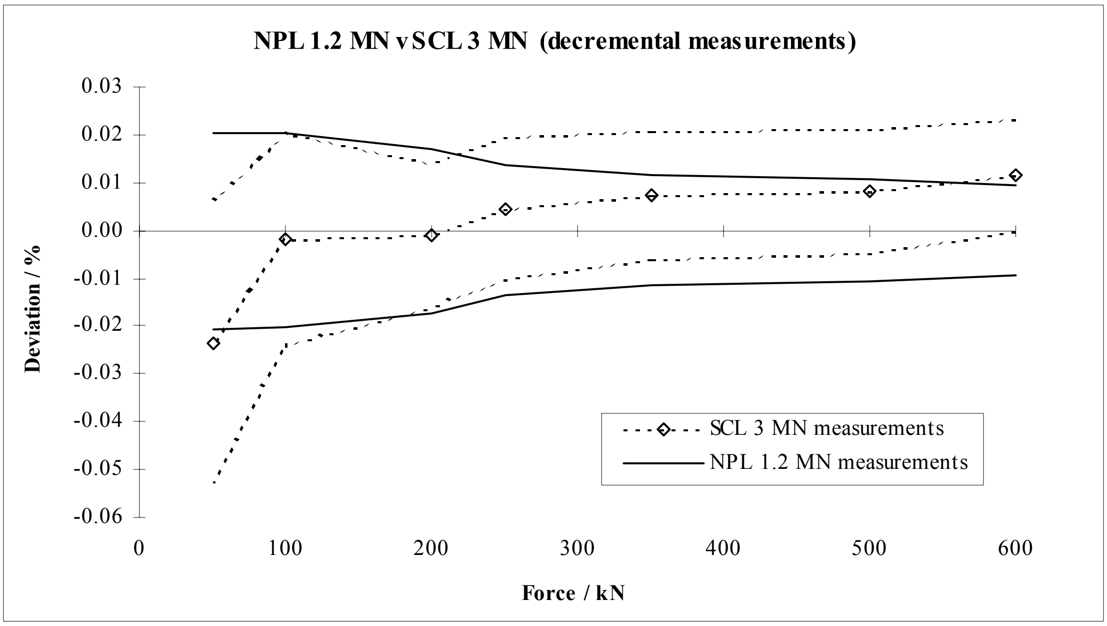



Figure 24: NPL 1.2 MN v SCL 3 MN machine for decremental forces

### 6.4.2 Results using three 1.2 MN load cells

The following graphs compare the forces measured in the force standard machines. The overall uncertainty of forces measured by the 1 MN load cell was calculated from the measurements made in the NPL 1.2 MN force standard machine (see section 4.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the SCL 3 MN force standard machine from those measured in the NPL 1.2 MN force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the SCL 3 MN force standard machine calculated using the equation on page 11.

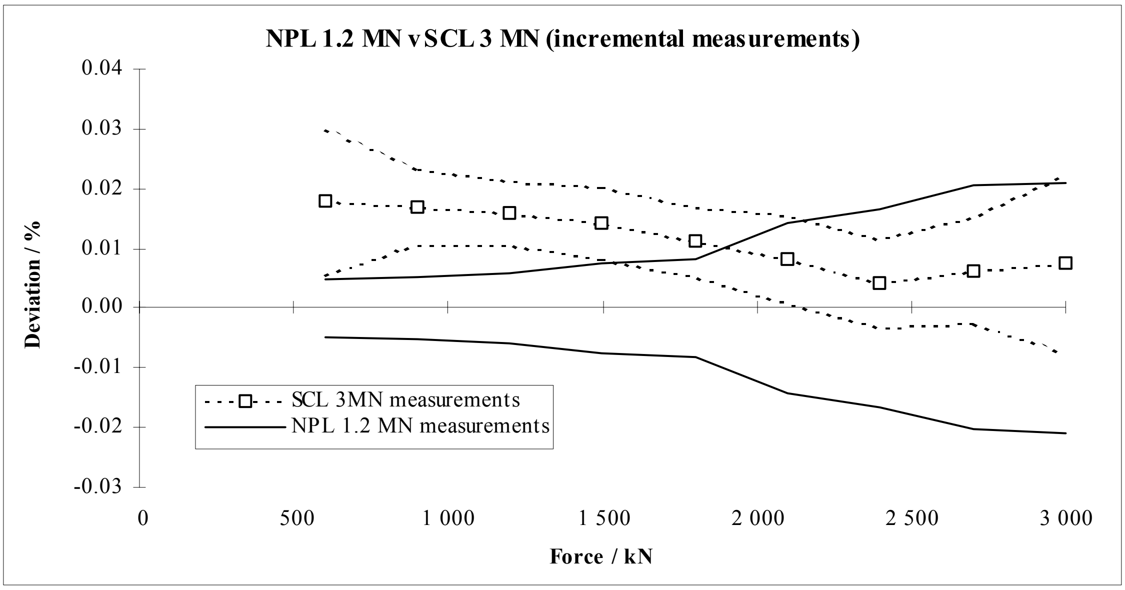



Figure 25: NPL 1.2 MN v SCL 3 MN machine for incremental forces

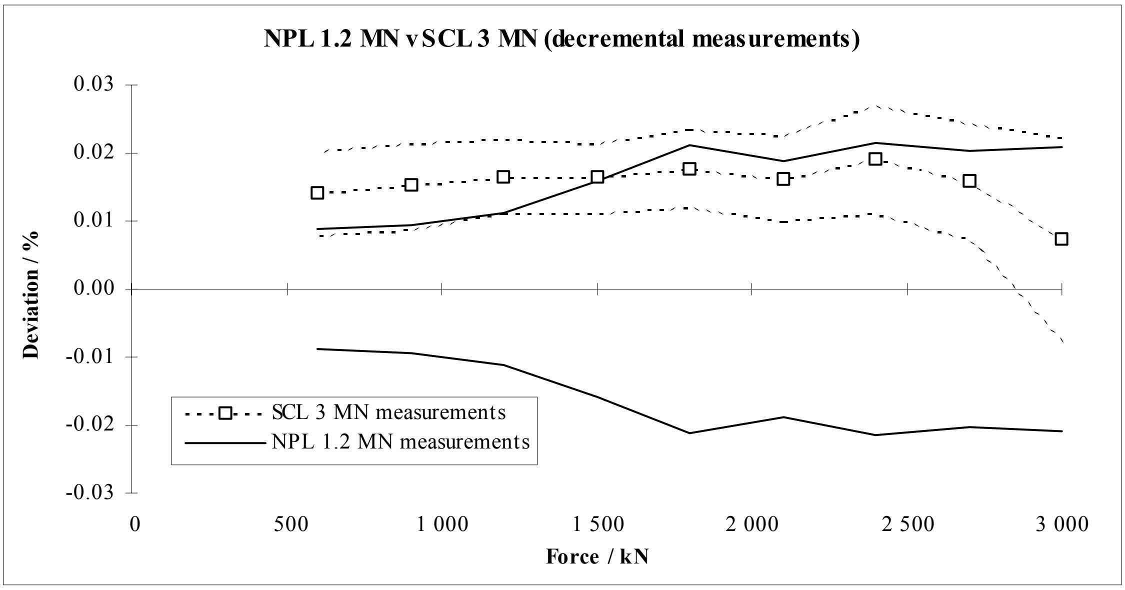



Figure 26: NPL 1.2 MN v SCL 3 MN machine for decremental forces

## 7. Results of intercomparison between NPL and NIM

The NIM's 20 MN machine is designed to apply different forces to those used to calibrate the load cells at NPL. A 5th order polynomial was fitted to the measurement results so that a comparison could be made between NPL, SCL, and NIM.

Sections 7.1 and 7.3 contain a summary of the measurements made at NIM. 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:

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

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

If the following criterion is satisfied, two machines agree within their uncertainty limits.

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

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 that of the measured deviation.

## 7.1 NIM (Lab 102) 1.1 MN deadweight machine

### 7.1.1 Results using the 1 MN load cell

| 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 |
|---|---|---|---|---|---|---|---|---|
| 120 | 0.245 029 | 120.005 | 0.005 | 0.004 | 0.017 | -0.012 | 0.021 | YES |
| 180 | 0.367 674 | 179.999 | -0.001 | 0.000 | 0.014 | -0.014 | 0.013 | YES |
| 240 | 0.490 324 | 240.000 | 0.000 | 0.000 | 0.013 | -0.013 | 0.013 | YES |
| 360 | 0.735 648 | 359.995 | -0.005 | -0.001 | 0.011 | -0.013 | 0.010 | YES |
| 480 | 0.980 985 | 479.994 | -0.006 | -0.001 | 0.010 | -0.011 | 0.009 | YES |
| 600 | 1.226 326 | 599.993 | -0.007 | -0.001 | 0.010 | -0.011 | 0.009 | YES |
| 480 | 0.981 026 | 480.014 | 0.014 | 0.003 | 0.011 | -0.008 | 0.013 | YES |
| 360 | 0.735 730 | 360.001 | 0.001 | 0.000 | 0.011 | -0.011 | 0.012 | YES |
| 240 | 0.490 404 | 240.000 | 0.000 | 0.000 | 0.014 | -0.014 | 0.014 | YES |
| 180 | 0.367 726 | 179.989 | -0.011 | -0.006 | 0.017 | -0.023 | 0.011 | YES |
| 120 | 0.245 060 | 119.992 | -0.008 | -0.006 | 0.020 | -0.027 | 0.014 | YES |

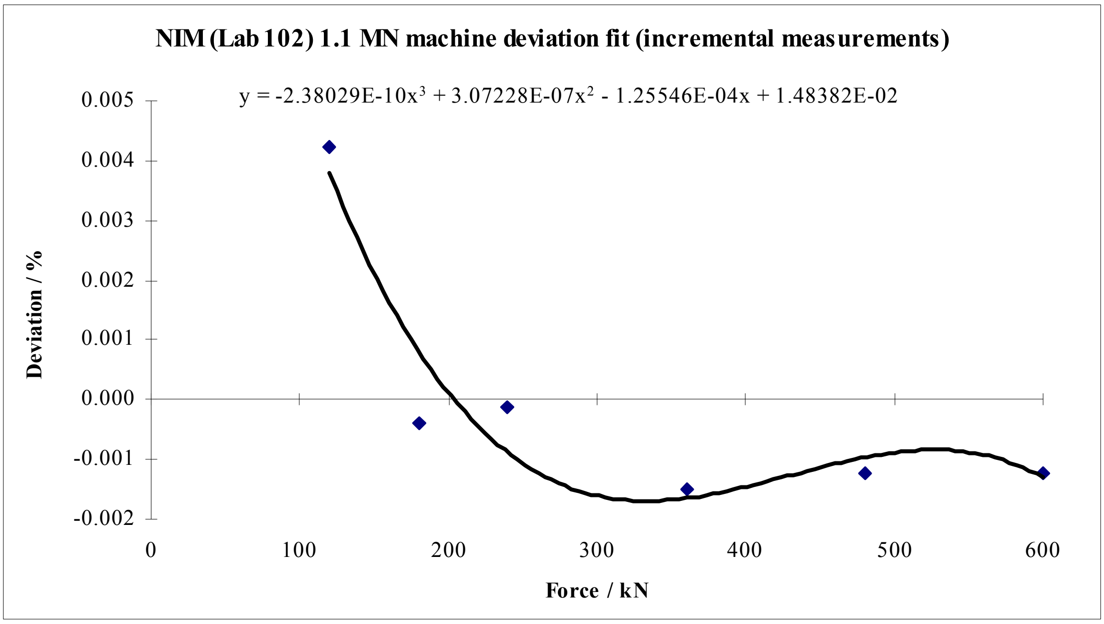



Figure 27: NIM (Lab 102) 1.1 MN machine deviation fit for incremental forces

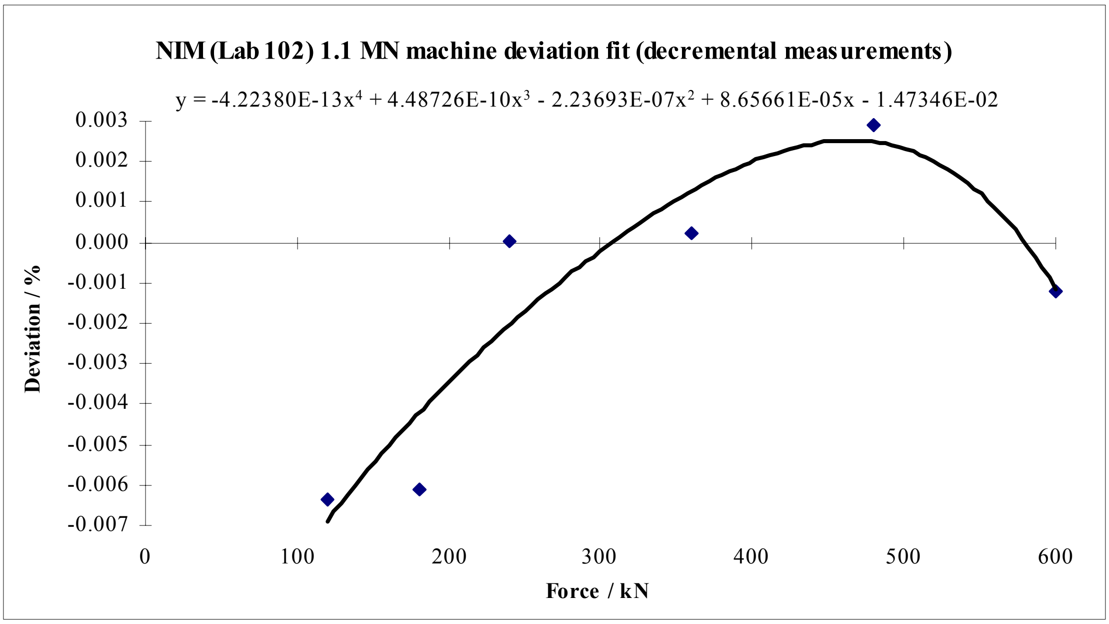



Figure 28: NIM (Lab 102) 1.1 MN machine deviation fit for decremental forces

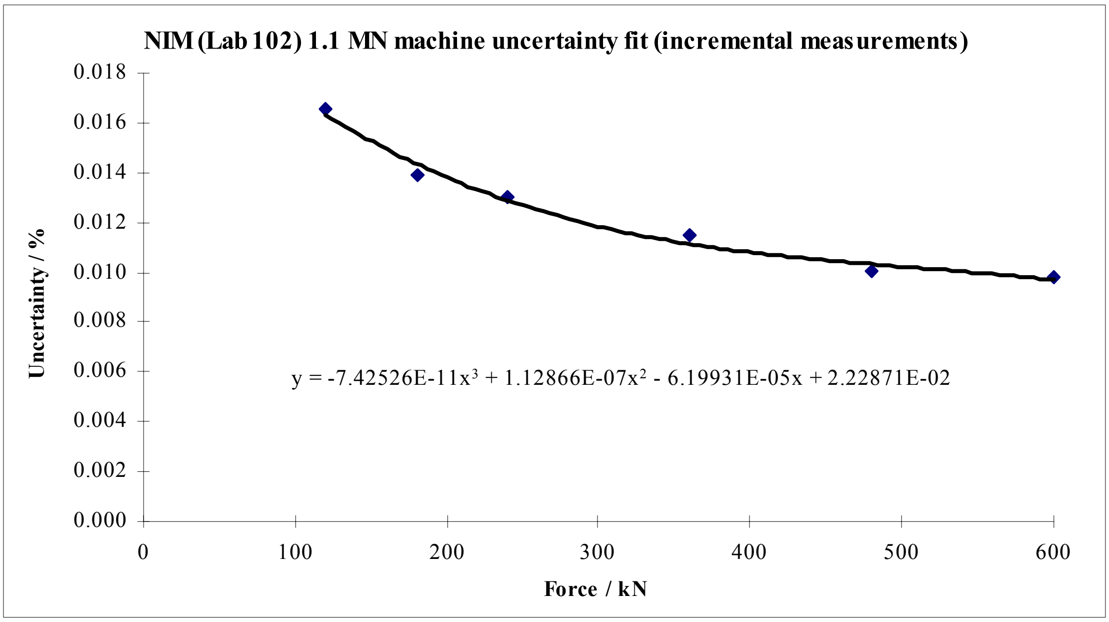



Figure 29: NIM (Lab 102) 1.1 MN machine uncertainty fit for incremental forces

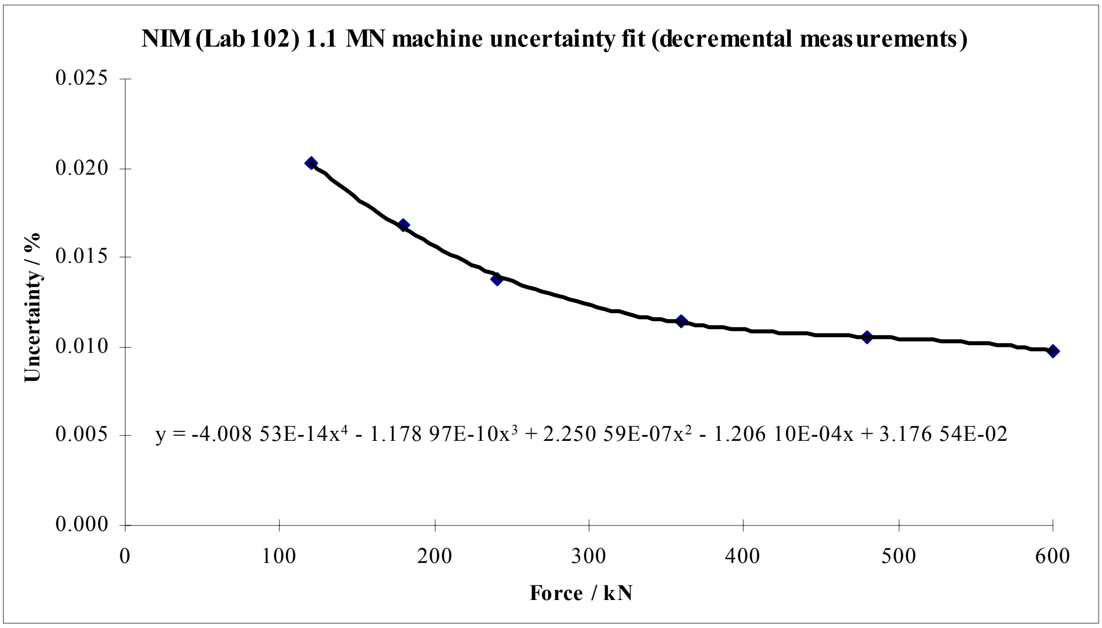



Figure 30: NIM (Lab 102) 1.1 MN machine uncertainty fit for decremental forces

## 7.2 Comparison of results between the NPL 1.2 MN machine and the NIM (Lab 102) 1.1 MN machine

### 7.2.1 Results using the 1 MN load cell

The following graphs compare the forces measured in the force standard machines. The overall uncertainty of forces measured by the 1 MN load cell was calculated from the measurements made in the NPL 1.2 MN force standard machine (see section 4.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NIM (Lab 102) 1.1 MN force standard machine from those measured in the NPL 1.2 MN force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NIM (Lab 102) 1.1 MN force standard machine calculated using the equation on page 25.

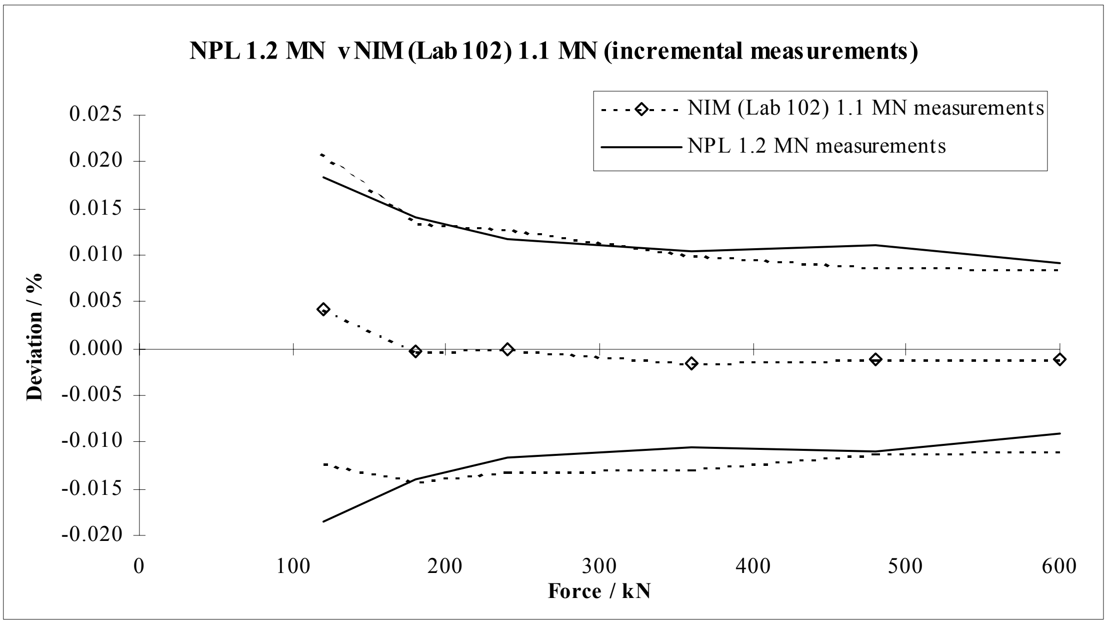



Figure 31: NPL 1.2 MN v NIM (Lab 102) 1.1 MN machine for incremental forces

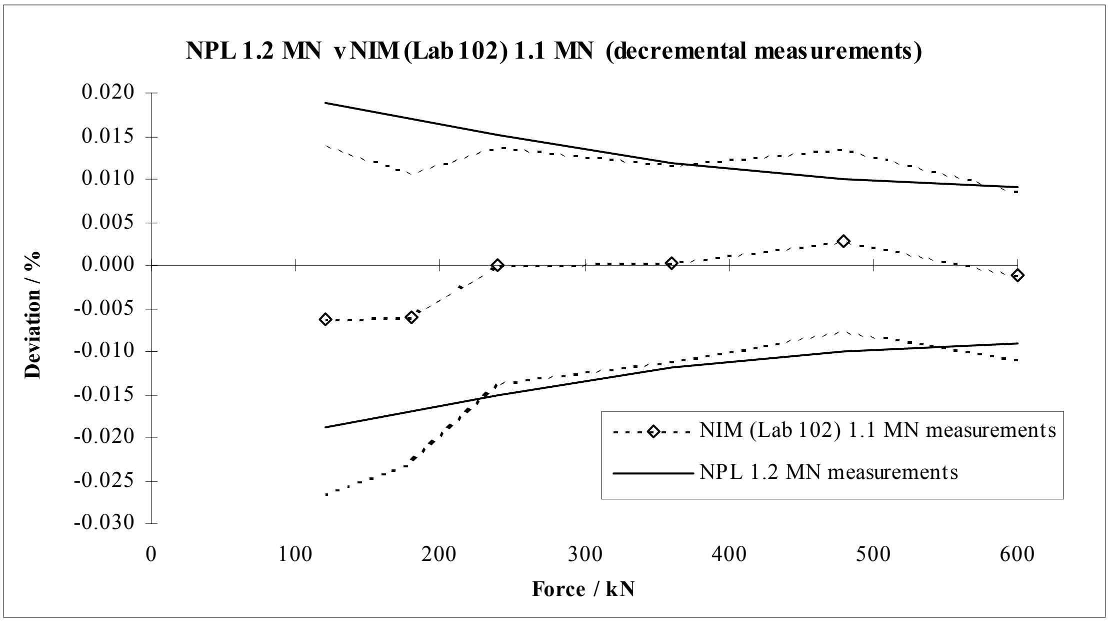



Figure 32: NPL 1.2 MN v NIM (Lab 102) 1.1 MN machine for decremental forces

## 7.3 NIM 20 MN hydraulic amplification machine

The nominal forces generated by the NIM 20 MN force standard machine differ from those generated by the NPL 1.2 MN force standard machine. So that the measurements made at NPL, SCL, and NIM could be compared, 5th order polynomials were fitted to the measured load cell outputs.

### 7.3.1 Results using three 1.2 MN load cells

| 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 |
|---|---|---|---|---|---|---|---|---|
| 500 | 0.301 200 | 500.020 | 0.020 | 0.004 | 0.060 | -0.056 | 0.064 | YES |
| 1 000 | 0.602 032 | 1 000.058 | 0.058 | 0.006 | 0.033 | -0.027 | 0.039 | YES |
| 1 500 | 0.902 532 | 1 500.173 | 0.173 | 0.012 | 0.020 | -0.008 | 0.031 | YES |
| 2 000 | 1.202 611 | 2 000.208 | 0.208 | 0.010 | 0.020 | -0.010 | 0.031 | YES |
| 2 500 | 1.502 329 | 2 500.329 | 0.329 | 0.013 | 0.022 | -0.009 | 0.035 | YES |
| 3 000 | 1.801 579 | 3 000.364 | 0.364 | 0.012 | 0.022 | -0.010 | 0.034 | YES |
| 2 500 | 1.502 367 | 2 500.303 | 0.303 | 0.012 | 0.023 | -0.011 | 0.035 | YES |
| 2 000 | 1.202 686 | 2 000.088 | 0.088 | 0.004 | 0.023 | -0.018 | 0.027 | YES |
| 1 500 | 0.902 745 | 1 500.134 | 0.134 | 0.009 | 0.027 | -0.018 | 0.036 | YES |
| 1 000 | 0.602 250 | 999.996 | -0.004 | 0.000 | 0.025 | -0.025 | 0.024 | YES |
| 500 | 0.301 279 | 499.857 | -0.143 | -0.029 | 0.043 | -0.072 | 0.015 | YES |

Figures 33 and 34 show the polynomial equation used to give the actual force measured from the mean measured output voltage ratios, where different nominal forces were applied in the two standards laboratories.

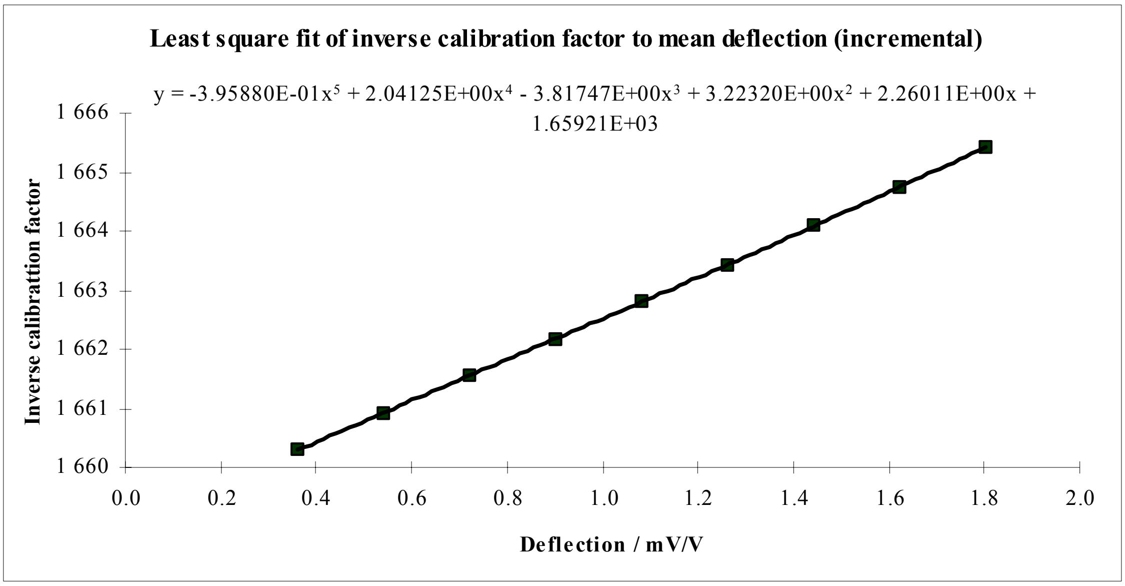



Figure 33: Least squares fit of inverse calibration factor to mean deflection for incremental forces

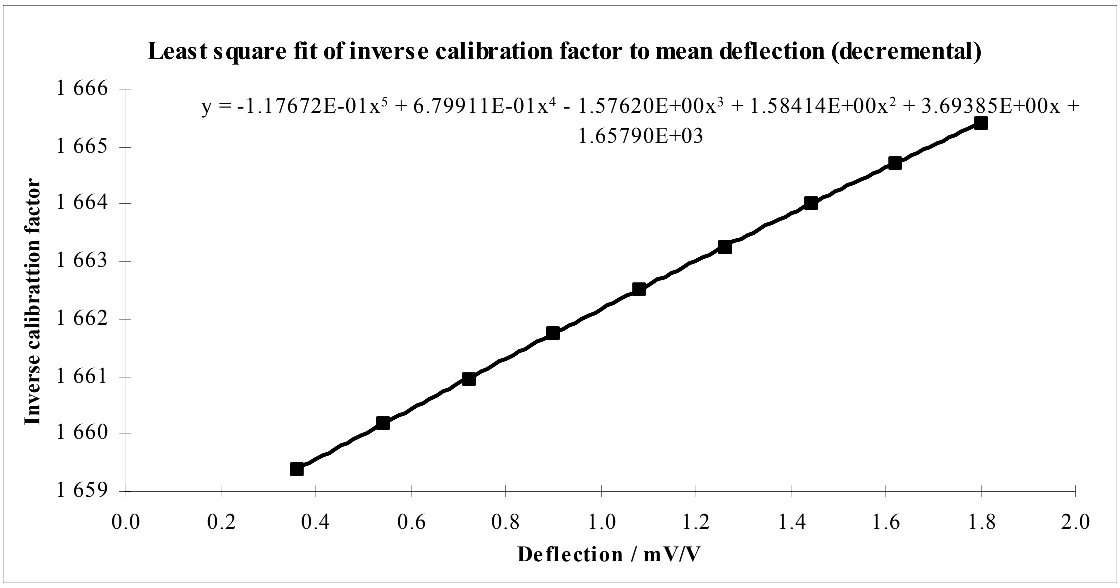



Figure 34: Least squares fit of inverse calibration factor to mean deflection for decremental forces

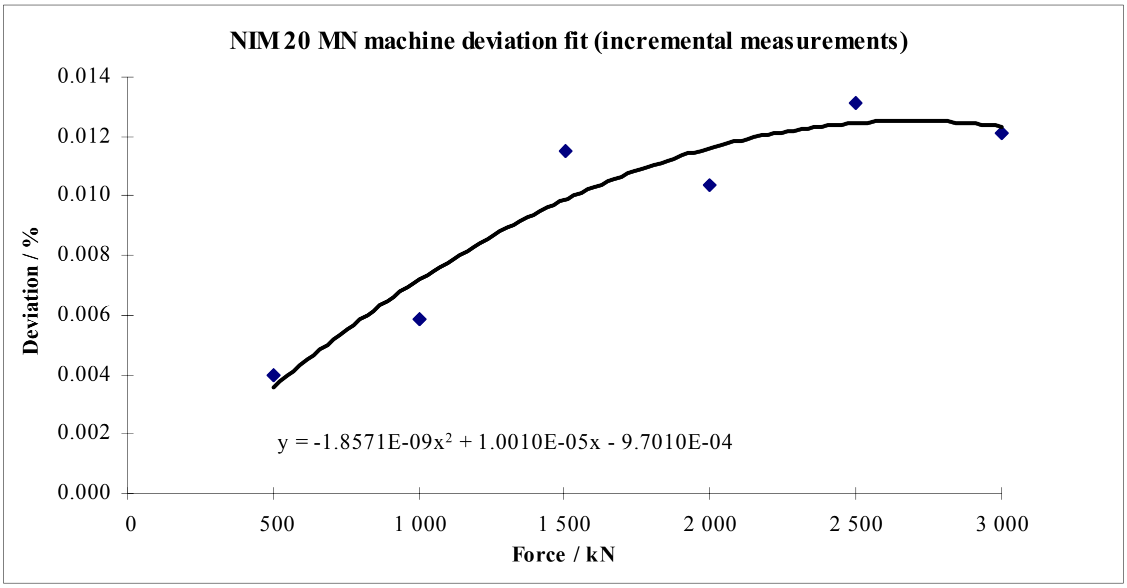



Figure 35: NIM 20 MN machine deviation fit for incremental forces

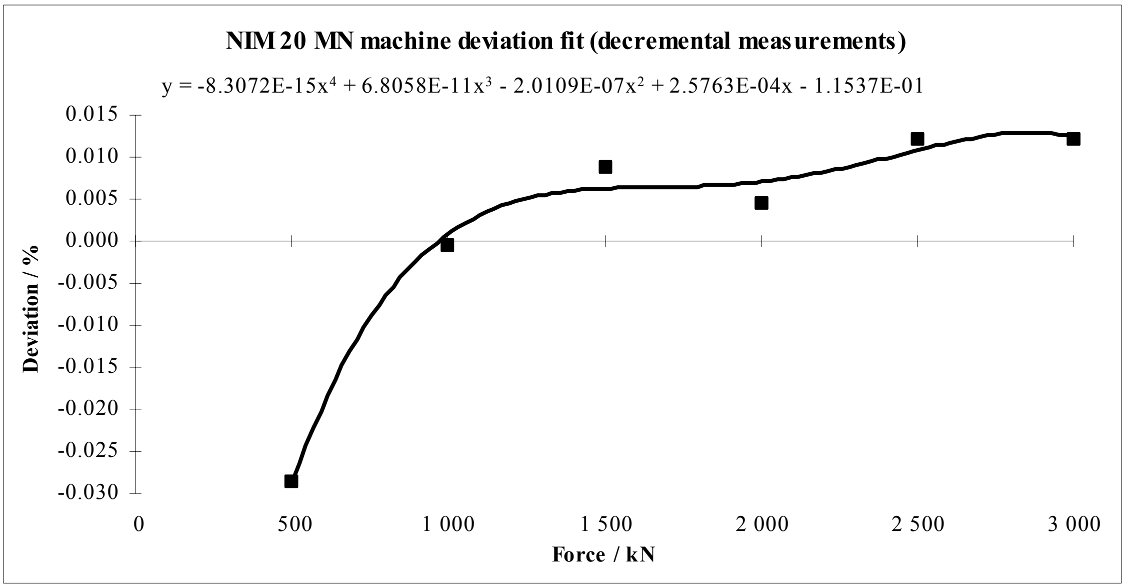



Figure 36: NIM 20 MN machine deviation fit for decremental forces

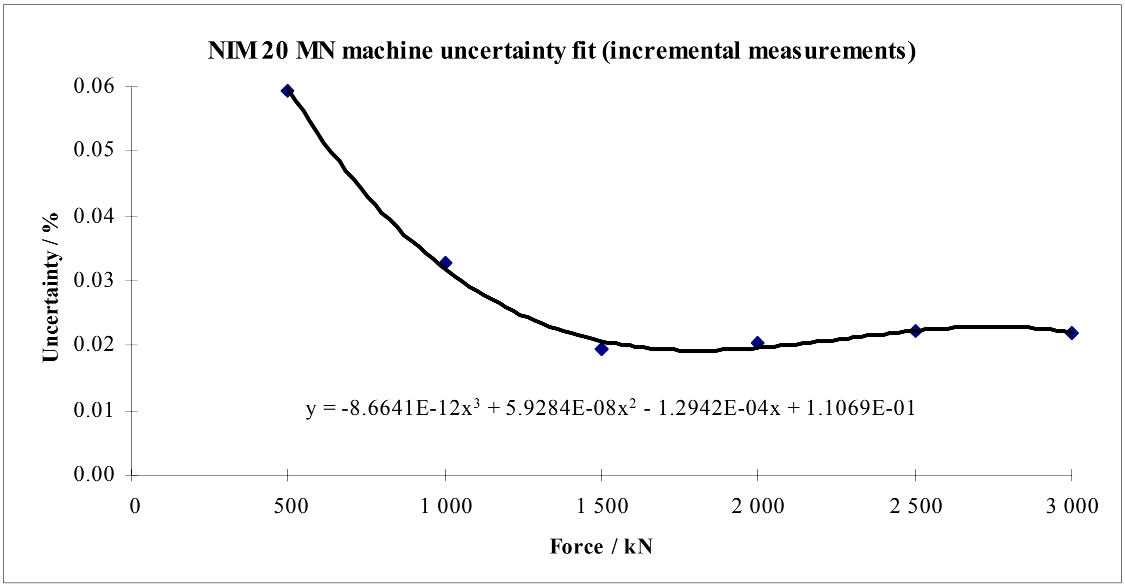



Figure 37: NIM 20 MN machine uncertainty fit for increasing forces

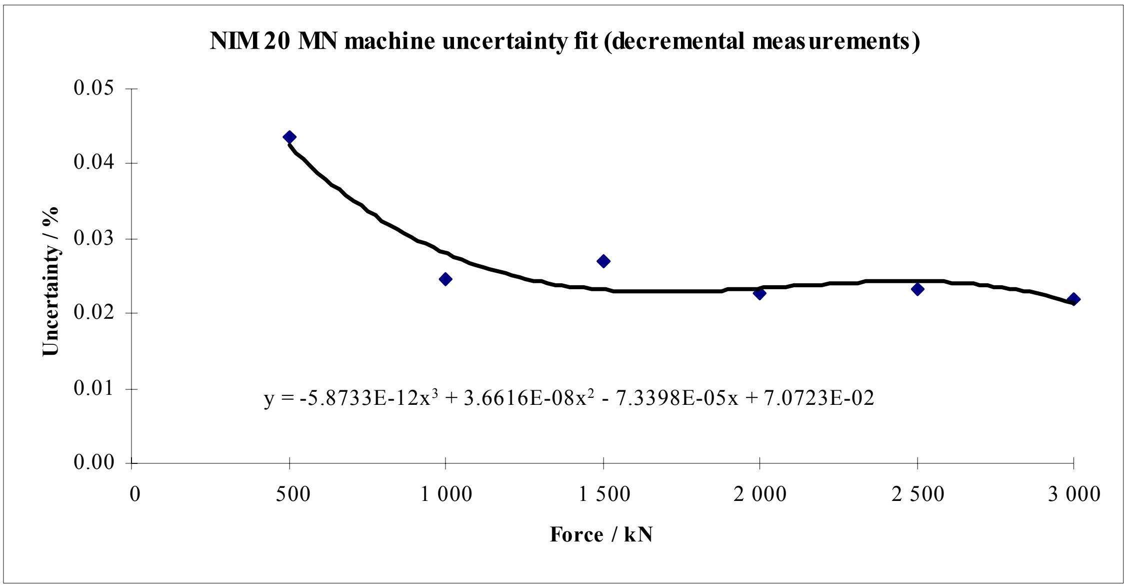



Figure 38: NIM 20 MN machine uncertainty fit for decreasing forces

## 7.4 Comparison of results between the NPL 1.2 MN machine and the NIM 20 MN machine

### 7.4.1 Results using three 1.2 MN load cells

The following graphs compare the forces measured in the force standard machines. The overall uncertainty of forces measured by the 1 MN load cell was calculated from the measurements made in the NPL 1.2 MN force standard machine (see section 4.1). These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NIM 20 MN force standard machine from those measured in the NPL 1.2 MN force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NIM 20 MN force standard machine calculated using the equation on page 25.

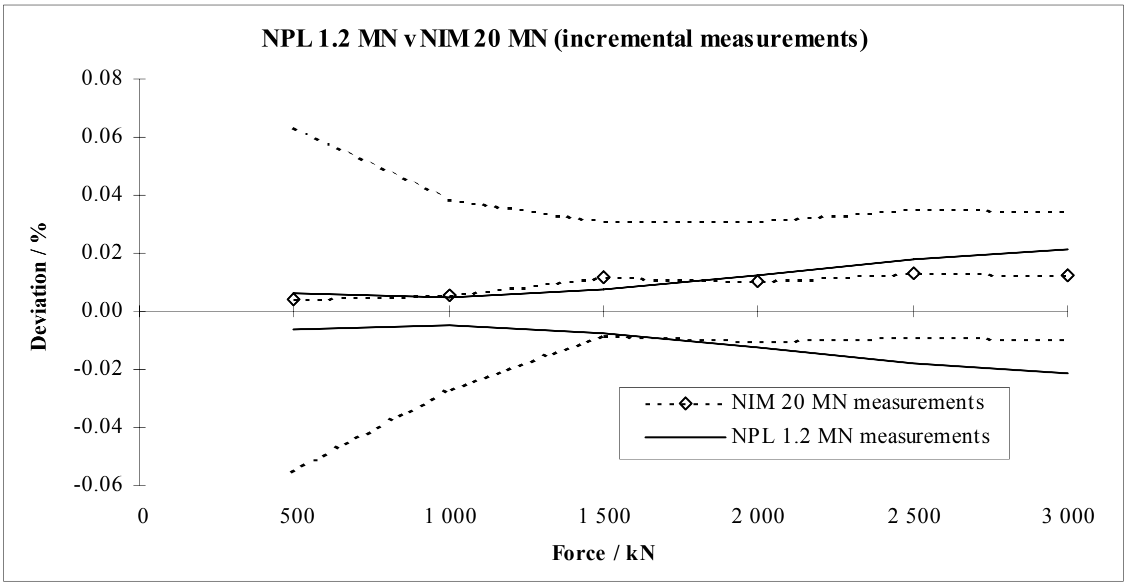



Figure 39: NPL 1.2 MN v NIM 20 MN machine for incremental forces

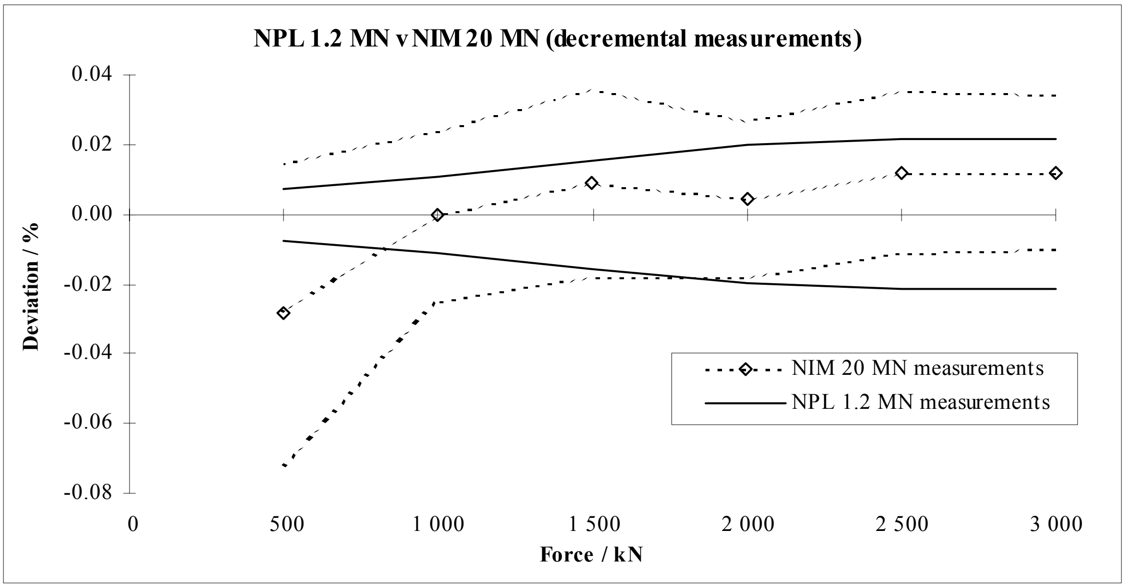



Figure 40: NPL 1.2 MN v NIM 20 MN machine for decremental forces

# 8. Comparison between SCL and NIM

Using the measurements obtained at both SCL and NIM, a comparison of the deviations from the nominal forces could be made.

The first two graphs, of each set of four, compare the forces measured in the force standard machines. The overall uncertainties of the forces measured by the 1 MN load cell were calculated from the measurements made in the NIM force standard machine. These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the SCL force standard machine from those measured in the NIM force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the SCL force standard machine calculated using the equation on page 11.

The last two graphs, of each set of four, compare the forces measured in the force standard machines. The overall uncertainties of the forces measured by the 1 MN load cell were calculated from the measurements made in the SCL force standard. These are represented by the solid lines. The central dotted line shows the deviation of the forces measured in the NIM force standard machine from those measured in the SCL force standard machine. The two outer dotted lines show the uncertainty bounds for the forces measured in the NIM force standard machine calculated using the equation on page 11.

## 8.1 SCL 600 kN and NIM (lab 102) 1.1 MN hydraulic amplification machines

### 8.1.1 Results using the 1 MN load cell

| nominal | | uncertainty | | | | | | agreement |
|---|---|---|---|---|---|---|---|---|
| Force kN | deviation % | NIM 1.1 MN | min % | max % | SCL 600 kN | min % | max % | between machines |
| 120 | -0.006 | 0.017 | -0.017 | 0.017 | 0.020 | -0.026 | 0.014 | YES |
| 180 | -0.003 | 0.014 | -0.014 | 0.014 | 0.016 | -0.019 | 0.014 | YES |
| 240 | -0.004 | 0.013 | -0.013 | 0.013 | 0.014 | -0.018 | 0.009 | YES |
| 360 | -0.006 | 0.011 | -0.011 | 0.011 | 0.011 | -0.017 | 0.005 | YES |
| 480 | -0.010 | 0.010 | -0.010 | 0.010 | 0.011 | -0.020 | 0.001 | YES |
| 600 | -0.013 | 0.010 | -0.010 | 0.010 | 0.010 | -0.023 | -0.004 | YES |
| 480 | -0.011 | 0.011 | -0.011 | 0.011 | 0.011 | -0.023 | 0.000 | YES |
| 360 | -0.003 | 0.011 | -0.011 | 0.011 | 0.013 | -0.017 | 0.010 | YES |
| 240 | 0.000 | 0.014 | -0.014 | 0.014 | 0.017 | -0.017 | 0.017 | YES |
| 180 | 0.007 | 0.017 | -0.017 | 0.017 | 0.019 | -0.012 | 0.026 | YES |
| 120 | 0.008 | 0.020 | -0.020 | 0.020 | 0.021 | -0.013 | 0.028 | YES |

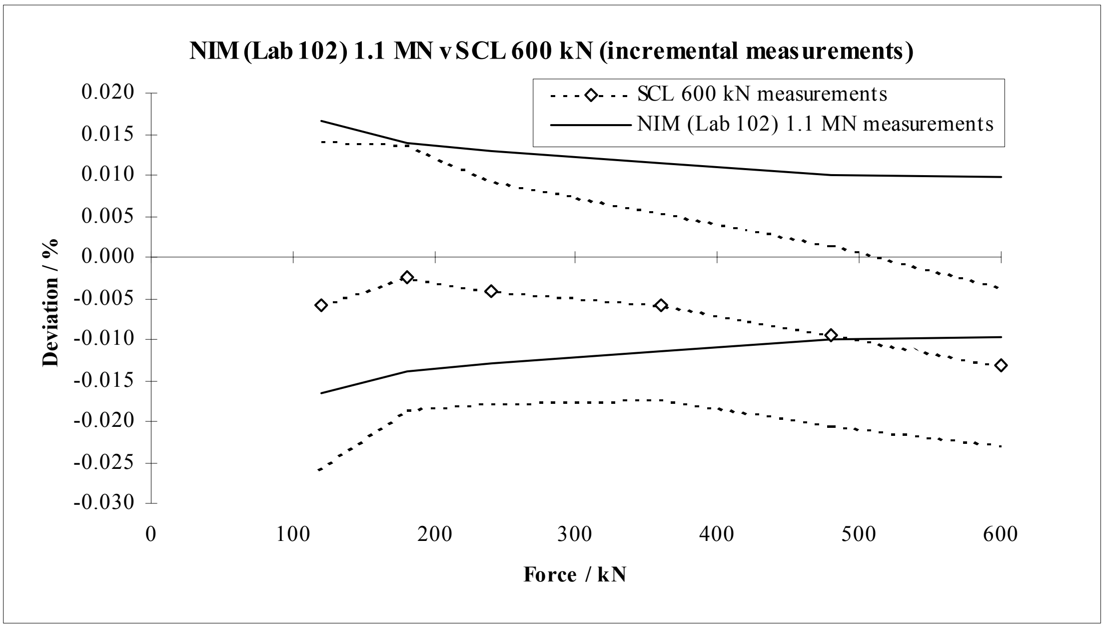



Figure 41: NIM (Lab 102) 1.1 MN v SCL 600 kN machine for incremental forces

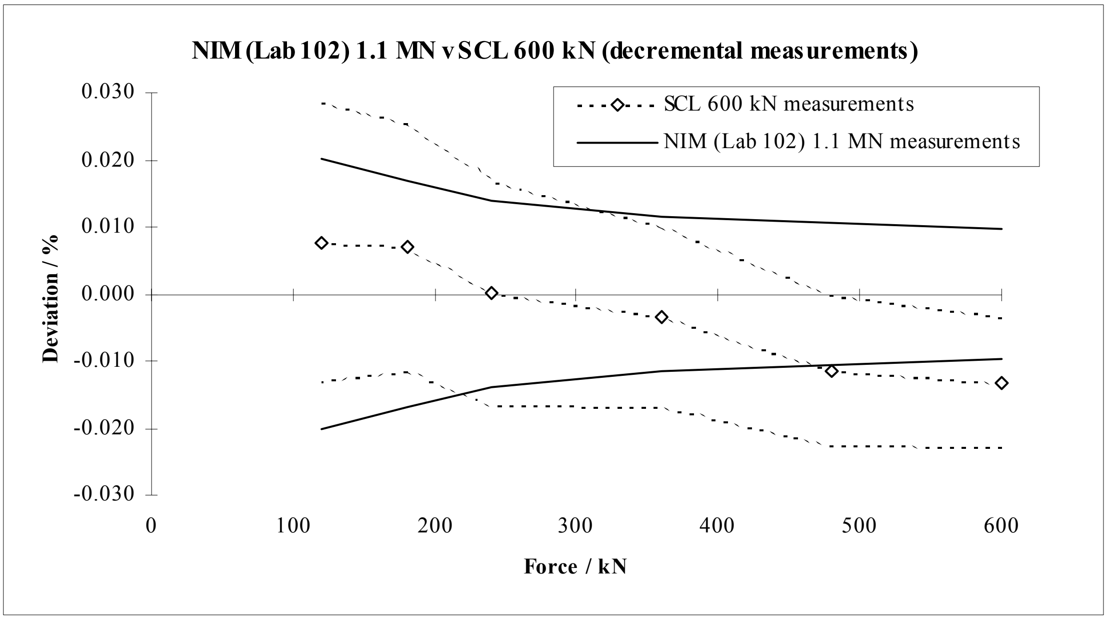



Figure 42: NIM (Lab 102) 1.1 MN v SCL 600 kN machine for decremental forces

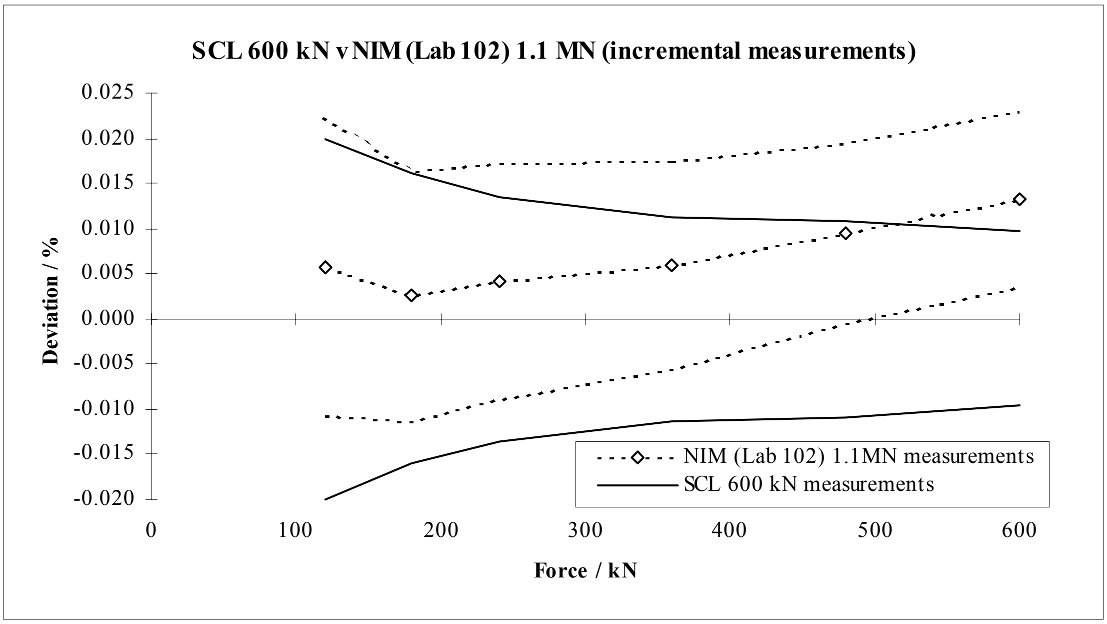



Figure 43: SCL 600 kN v NIM (Lab 102) 1.1 MN machine for incremental forces

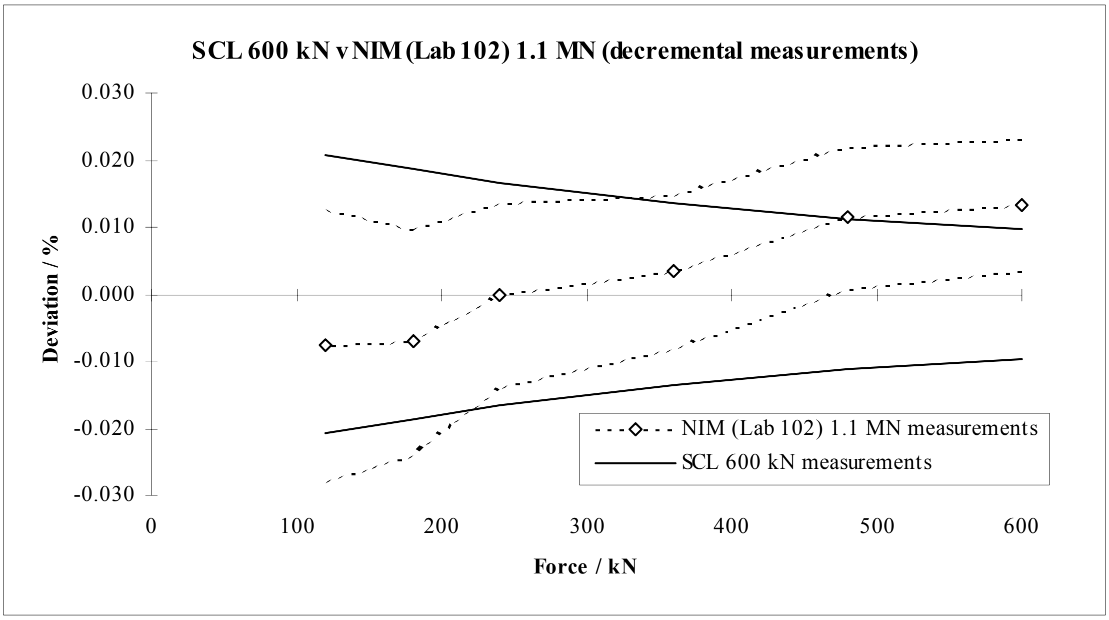



Figure 44: SCL 600 kN v NIM (Lab 102) 1.1 MN machine for decremental forces

## 8.2 SCL 3 MN and NIM (lab 102) 1.1 MN hydraulic amplification machines

### 8.2.1 Results using the 1 MN load cell

| nominal Force kN | deviation % | uncertainty NIM 1.1 MN | min % | max % | SCL 3 MN | min % | max % | agreement between machines |
|---|---|---|---|---|---|---|---|---|
| 120 | 0.007 | 0.017 | -0.017 | 0.017 | 0.022 | -0.015 | 0.029 | YES |
| 180 | 0.014 | 0.014 | -0.014 | 0.014 | 0.018 | -0.004 | 0.032 | YES |
| 240 | 0.013 | 0.013 | -0.013 | 0.013 | 0.016 | -0.003 | 0.028 | YES |
| 360 | 0.012 | 0.011 | -0.011 | 0.011 | 0.014 | -0.002 | 0.026 | YES |
| 480 | 0.015 | 0.010 | -0.010 | 0.010 | 0.014 | 0.001 | 0.028 | YES |
| 600 | 0.013 | 0.010 | -0.010 | 0.010 | 0.011 | 0.001 | 0.024 | YES |
| 480 | 0.004 | 0.011 | -0.011 | 0.011 | 0.014 | -0.010 | 0.017 | YES |
| 360 | 0.007 | 0.011 | -0.011 | 0.011 | 0.013 | -0.007 | 0.020 | YES |
| 240 | 0.005 | 0.014 | -0.014 | 0.014 | 0.014 | -0.009 | 0.019 | YES |
| 180 | 0.007 | 0.017 | -0.017 | 0.017 | 0.017 | -0.009 | 0.024 | YES |
| 120 | 0.000 | 0.020 | -0.020 | 0.020 | 0.021 | -0.020 | 0.021 | YES |

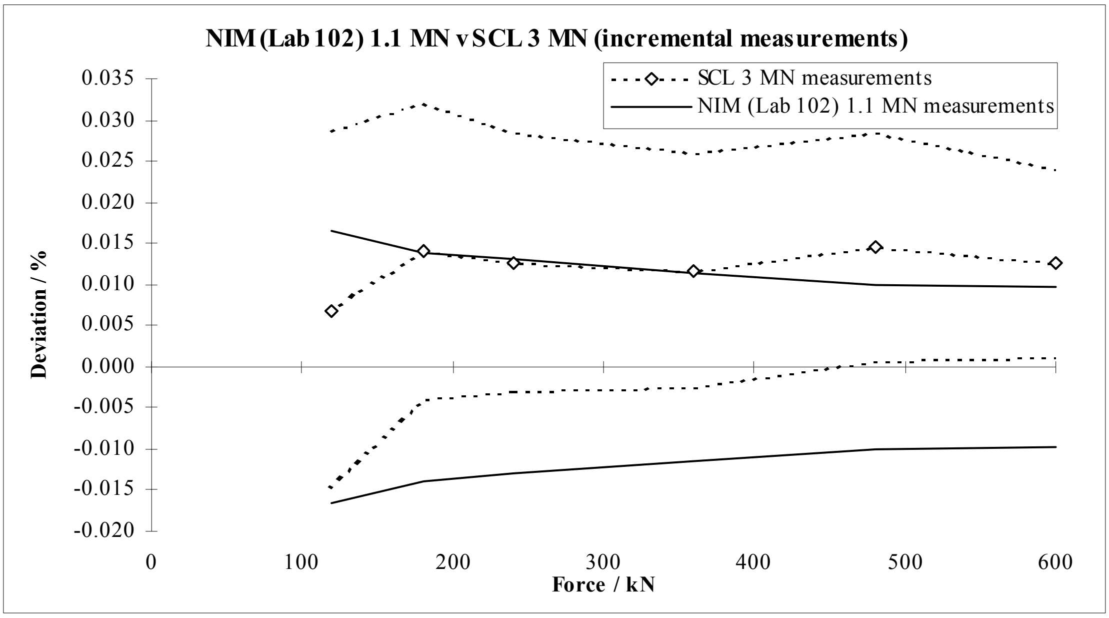



Figure 45: NIM (Lab 102) 1.1 MN v SCL 3 MN machine for incremental forces

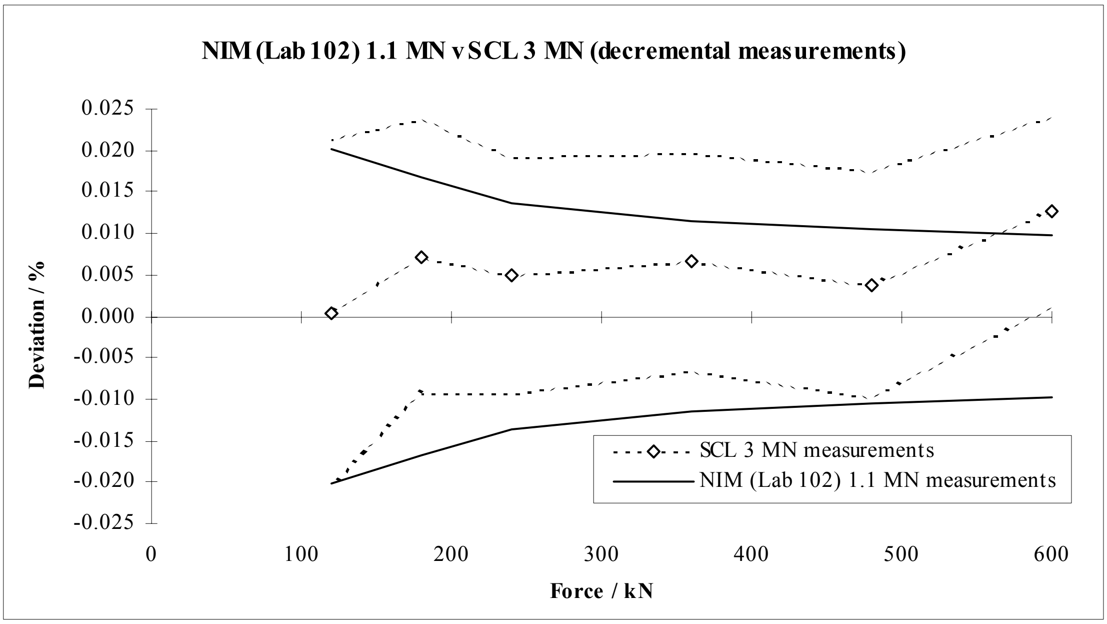



Figure 46: NIM (Lab 102) 1.1 MN v SCL 3 MN machine for decremental forces

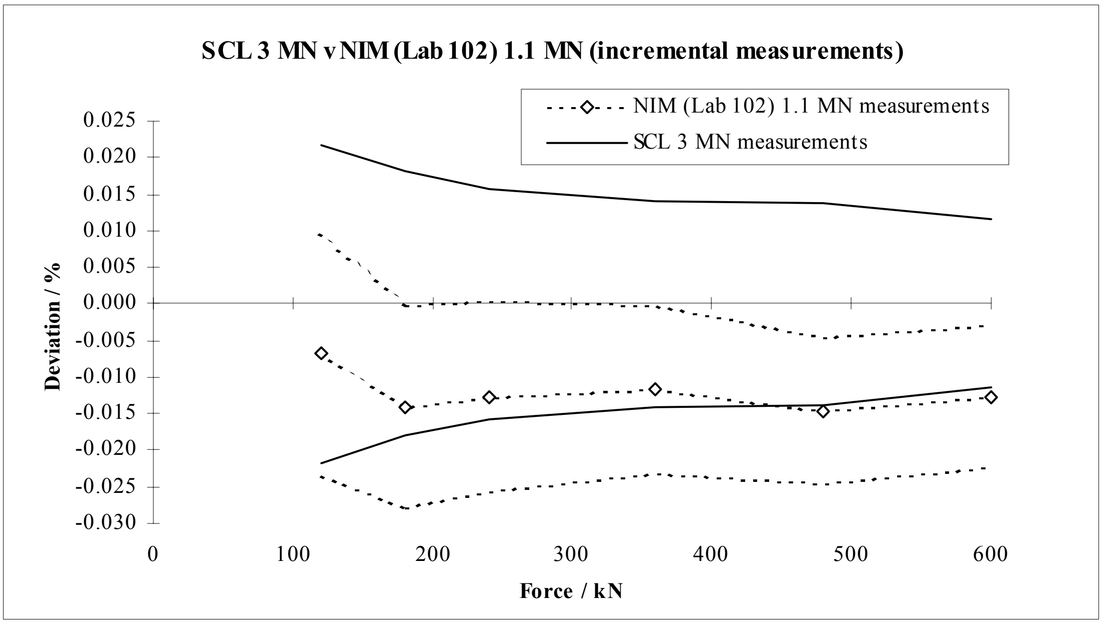



Figure 47: SCL 3 MN v NIM (Lab 102) 1.1 MN machine for incremental forces

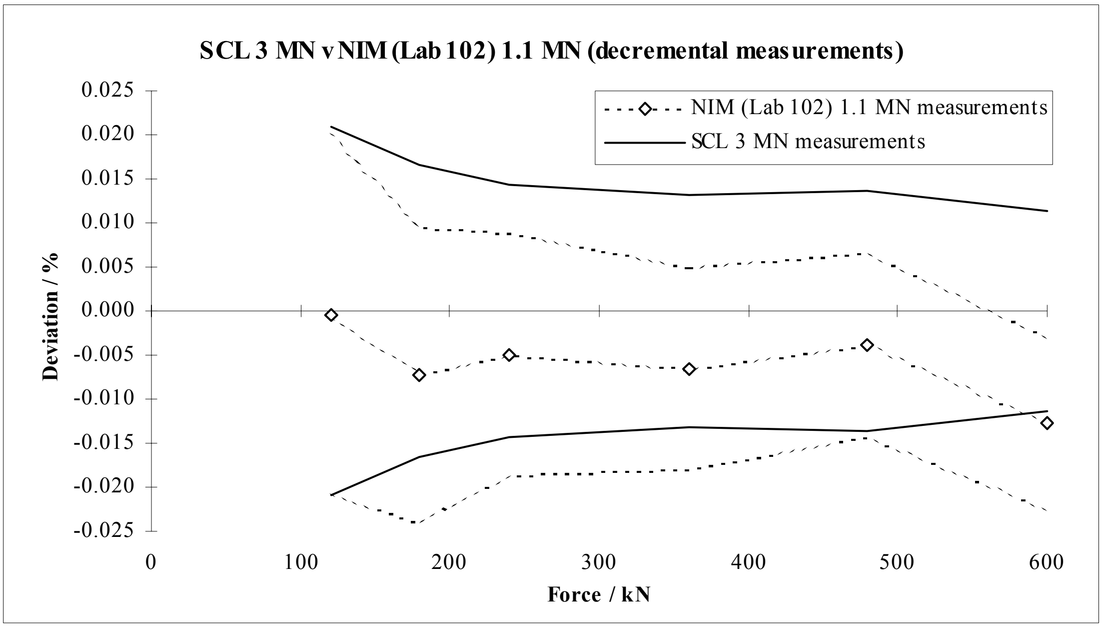



Figure 48: SCL 3 MN v NIM (Lab 102) 1.1 MN machine for decremental forces

## 8.3 SCL 3 MN and NIM 20 MN hydraulic amplification machines

### 8.3.1 Results using three 1.2 MN load cells

| nominal Force kN | deviation % | uncertainty SCL 3 MN | min % | max % | NIM 20 MN | min % | max % | agreement between machines |
|---|---|---|---|---|---|---|---|---|
| 600 | -0.013 | 0.012 | -0.012 | 0.012 | 0.053 | -0.066 | 0.039 | YES |
| 900 | -0.010 | 0.006 | -0.006 | 0.006 | 0.036 | -0.046 | 0.026 | YES |
| 1 200 | -0.008 | 0.005 | -0.005 | 0.005 | 0.026 | -0.033 | 0.018 | YES |
| 1 500 | -0.004 | 0.006 | -0.006 | 0.006 | 0.021 | -0.025 | 0.016 | YES |
| 1 800 | 0.000 | 0.006 | -0.006 | 0.006 | 0.019 | -0.019 | 0.019 | YES |
| 2 100 | 0.004 | 0.007 | -0.007 | 0.007 | 0.020 | -0.016 | 0.024 | YES |
| 2 400 | 0.008 | 0.007 | -0.007 | 0.007 | 0.022 | -0.013 | 0.030 | YES |
| 2 700 | 0.006 | 0.009 | -0.009 | 0.009 | 0.023 | -0.017 | 0.029 | YES |
| 3 000 | 0.005 | 0.015 | -0.015 | 0.015 | 0.022 | -0.017 | 0.027 | YES |
| 2 700 | -0.003 | 0.009 | -0.009 | 0.009 | 0.024 | -0.027 | 0.020 | YES |
| 2 400 | -0.009 | 0.008 | -0.008 | 0.008 | 0.024 | -0.034 | 0.015 | YES |
| 2 100 | -0.009 | 0.006 | -0.006 | 0.006 | 0.024 | -0.032 | 0.015 | YES |
| 1 800 | -0.011 | 0.006 | -0.006 | 0.006 | 0.023 | -0.034 | 0.012 | YES |
| 1 500 | -0.010 | 0.005 | -0.005 | 0.005 | 0.023 | -0.033 | 0.013 | YES |
| 1 200 | -0.012 | 0.006 | -0.006 | 0.006 | 0.025 | -0.037 | 0.013 | YES |
| 900 | -0.017 | 0.006 | -0.006 | 0.006 | 0.030 | -0.047 | 0.013 | YES |
| 600 | -0.034 | 0.006 | -0.006 | 0.006 | 0.039 | -0.072 | 0.005 | YES |

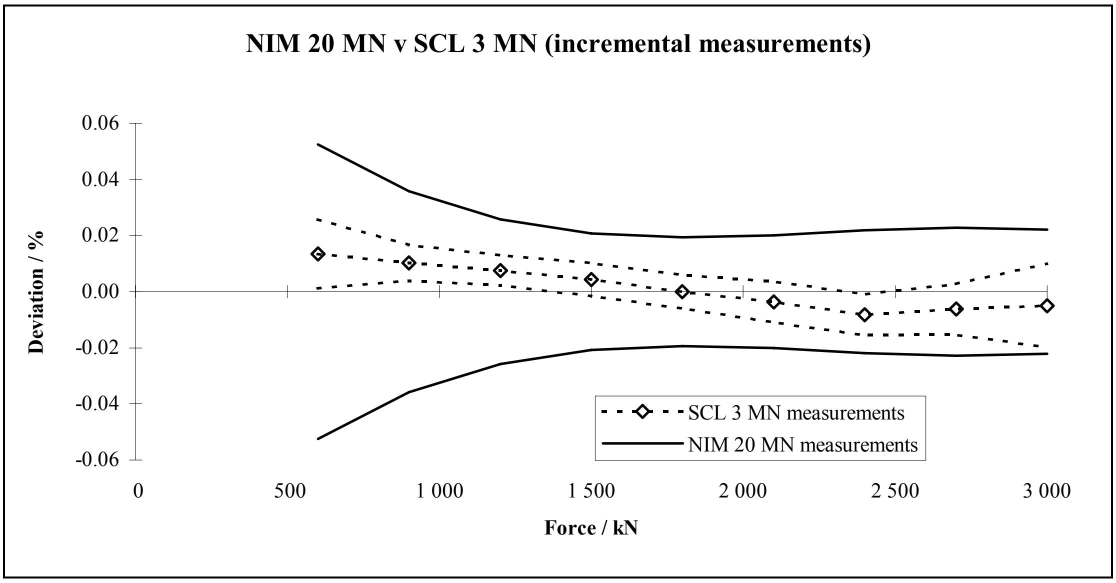



Figure 49: NIM 20 MN v SCL 3 MN machine for incremental forces

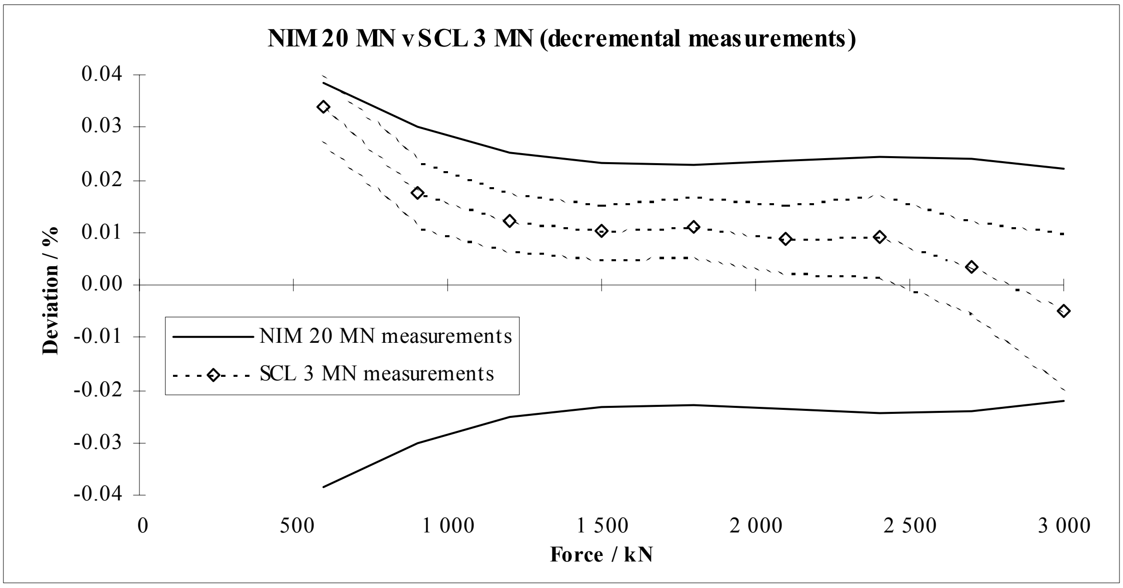



Figure 50: NIM 20 MN v SCL 3 MN machine for decremental forces

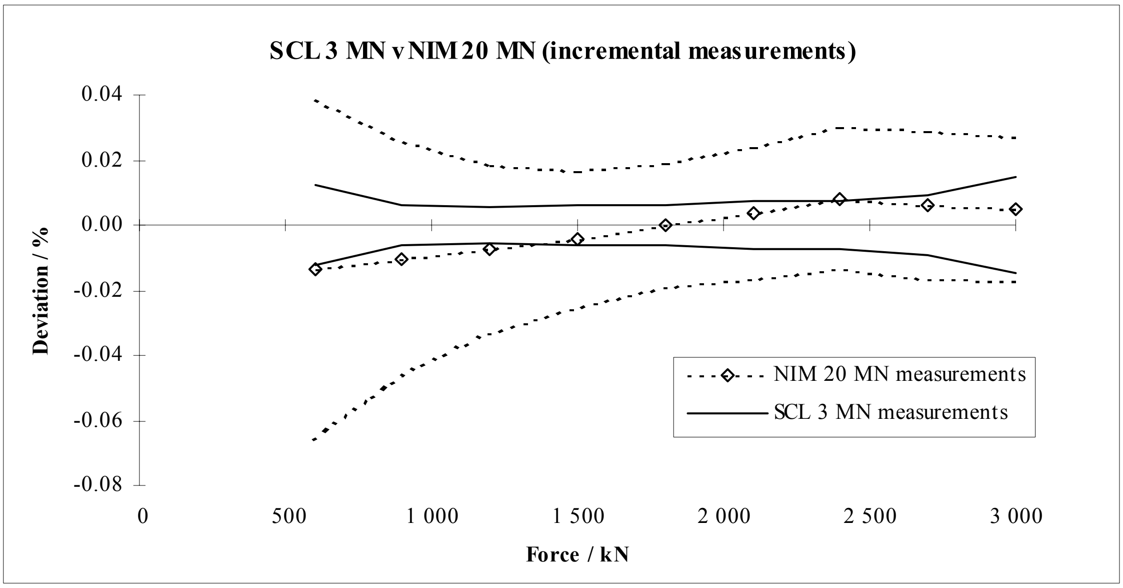



Figure 51: SCL 3 MN v NIM 20 MN machine for incremental forces

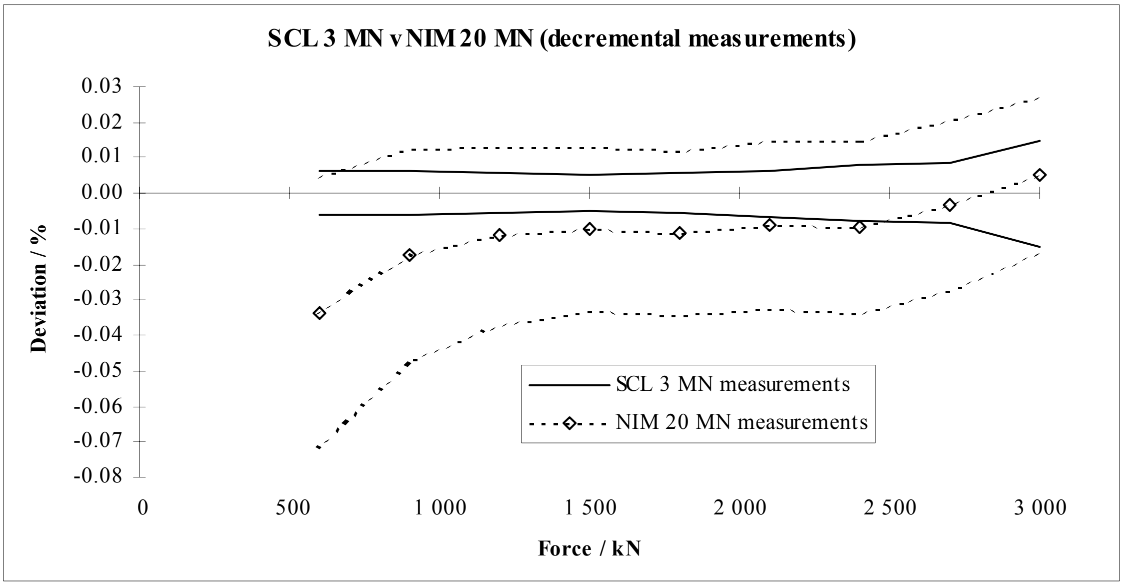



Figure 52: SCL 3 MN v NIM 20 MN machine for decremental forces

# 9. Observations

Many of the graphs show the measurements made in other force standard machines as deviations from the measurements made at NPL. This is because NPL was the pilot laboratory for the intercomparison and the load cells were calibrated at NPL before and after the calibrations in the other laboratories. This does not mean that the NPL measurements are the true values.

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.

During the calibration in the NIM (Lab 102) 1.1 MN force standard machine, several minor problems interrupted the timed loading sequence. This prevented measurement of hysteresis at the 120° and 240° positions. The reproducibility of the decremental forces was assumed to be the same as for the equivalent incremental forces. The deviations in the average forces measured by the NIM (Lab 102) 1.1 MN force standard machine compared with the NPL 1.2 MN force standard machine were within ±0.004 % for increasing forces and ±0.006 % for decreasing forces. If the timed loading sequence had not been interrupted, the decremental deviations may have been smaller.

The average forces measured in the NIM 20 MN force standard machine deviated from those measured in the NPL 1.2 MN force standard machine by less than ±0.013 % for both increasing and decreasing forces. The exception is the 500 kN decreasing force which had a deviation of ±0.029 %. There was no obvious reason for this. The deviation was repeatable, implying a systematic origin.

It is usually recommended that a load cell is not used below 40 % of its rated capacity for high-accuracy intercomparison work. Below this level they can be more sensitive to end loading conditions. The three parallel 1.2 MN load cells were used down to 500 kN (17 % of combined their rated capacity) so that the hysteresis of the machines could be measured.

## 10. Summary

The results showed that the forces generated by the force standard machines of the three laboratories agreed to better than: ±0.05 % for the hydraulic amplification force standard machines, and ±0.006 % for the deadweight force standard machines. The agreements were all within the calculated uncertainties of measurement. The differences between the forces measured in the force standard machines are summarised in the table below.

| Deviation of forces between the force standard machines | | | | | | | |
|---|---|---|---|---|---|---|---|
| Machine | stated Uncertainty | NPL 1.2 MN | | NIM (Lab 102) 1.1 MN | | NIM 20 MN | |
| | | Increasing | Decreasing | Increasing | Decreasing | Increasing | Decreasing |
| NPL 1.2 MN | ±0.001% | | | ±0.004% | ±0.006% | ±0.013% | ±0.012% (-0.029%)* |
| SCL 600 kN | ±0.02% | ±0.015% | ±0.010% | ±0.013% | 0.011% | | |
| SCL 3 MN | ±0.05% | ±0.018% | ±0.023% | ±0.015% | 0.007% | ±0.013% | ±0.034% |
| NIM (Lab 102) 1.1 MN | ±0.002% | ±0.004% | ±0.006% | | | | |
| NIM 20 MN | ±0.01% | ±0.013% | ±0.012% (-0.029%)* | | | | |

* Deviation for the 500 kN point

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## 12. References


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