3 Bar Versus 2 Bar Universal Calibrating Machines Comparison Test

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1. Introduction

There has been ongoing debate as to whether or not a hydraulic force machine that applies the force simultaneously to both the reference standard and the unit under test is more repeatable and reproducible when the force is applied and transferred with 3 bars versus 2 bars. The debate centers around alignment of the reference standard and the unit under test. There is no disagreement about the benefits of using a triangular configuration when using multiple load cells to weigh an object; however, there is a debate over any advantages that might be offered by using a 3 bar Universal Calibrating Machine (UCM) instead of a traditional 2 bar system. This paper provides test results for repeatability and reproducibility for a 2 bar UCM and a 3 bar UCM, showing the null hypothesis to be correct and proving that **there is not a difference** between either type of UCM. The article compares a per point uncertainty analysis for each style of machine using a Welch-Satterthwaite equation. Repeatability and reproducibility were examined using the same reference load cell, unit under test, hydraulic jack, Morehouse hydraulic power control, and HBM DMP40 indicators. Some of our key findings were the 2 bar UCM showed better repeatability on 7 of 10 points and the average CMC (Calibration and Measurement Capability) was higher on the 3 bar machine. When all aspects are considered, a 2 bar UCM will have the advantage as far as cost, lower tare weight, and easier calibration setups.

2. The Test

A load cell was tested in both a new 3 bar Universal Calibrating Machine (UCM) that was manufactured by Morehouse, and a 2 bar UCM that was manufactured by Morehouse and used successfully by industry and government labs for 50-plus years. Both machines used the same design criteria and had a capacity of 100,000 lbf. To minimize variables, the test was performed using as much as the same instrumentation as possible:

- The same hydraulic ram was used with both UCMs.
- The same Morehouse Hydraulic Power Control and hoses were used with both UCMs.
- The same reference standard and loading adapters were used with both UCMs.
- The same load cell was used as the UUT with both UCMs. The UUT was a 100,000 lbf Shear Web Load Cell 100,000 lbf Model SW30 Load Cell.
- Two HBM–DMP 40s: The same one was used with the reference standard and the UUT with both UCMs.

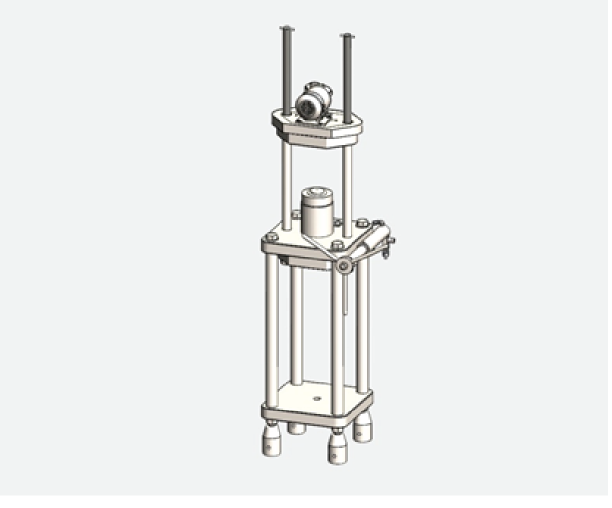


Figure 1. Design drawing of a Morehouse 2 Bar 100,000 lbf UCM.

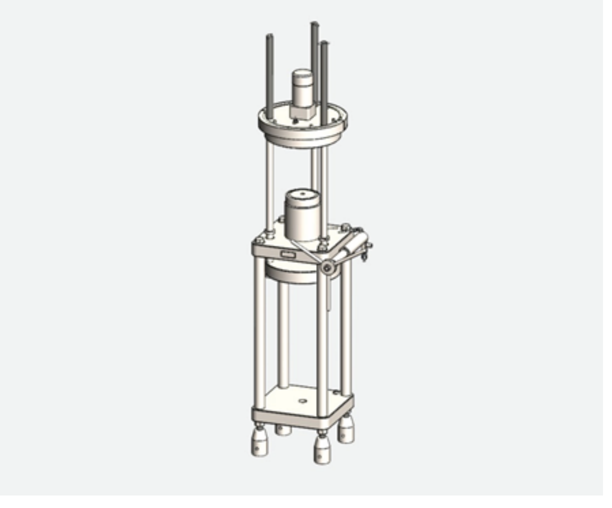


Figure 2. Design drawing of a Morehouse 3 Bar 100,000 lbf UCM.

3. The Reference Standard

A Morehouse Ultra Precision Load Cell calibrated using the Morehouse Force Calibration Laboratory's 120,000 lbf Dead Weight Primary Standard Force Machine was used as the reference standard. The measurement capability of the load cell was characterized using the following uncertainty contributors:

- Resolution of reference standard: 0.1 lbf
- ASTM E74 LLF (Converted to a pooled standard deviation): 2.471 lbf
- Resolution of UUT: 0.25 lbf
- Temperature effect on zero for both reference standard and UUT: 0.0015 % of rated output per 1° change in temperature
- CMC of 120,000 lbf Dead Weight Primary Standard Force Machine: 0.0016 %
- Repeatability, characterized per point (this is what varied between 2 and 3 bar UCM's)
- Stability was set to zero as the test between the UCMs was performed within a few days.

Figure 3. Morehouse 3 Bar 100,000 LBF UCM.

MODEL: ULTRA PRECISION
MOREHOUSE Load Cell, SERIAL NO. U-7660(HI)
100000.00 LBF Compression Calibrated to 100000.00 LBF
HBM DMP40 INDICATOR, SERIAL NO. 111320025

Calibration is in Accordance with ASTM E74-13
Ascending and Descending Compression DATA

Applied Load	Deflection Values Per ASTM Method 8.1B Interpolated Zero			Deviation From Fitted Curve			Values From Fitted Curve
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	
LBF	mV/V	mV/V	mV/V	mV/V	mV/V	mV/V	mV/V
2000	-0.08120	-0.08119	-0.08119	-0.00001	0.00000	0.00000	-0.08119
10000	-0.40602	-0.40605	-0.40601	0.00000	-0.00003	0.00001	-0.40602
20000	-0.81206	-0.81210	-0.81207	0.00002	-0.00002	0.00001	-0.81208
30000	-1.21815	-1.21819	-1.21819	0.00002	-0.00002	-0.00002	-1.21817
40000	-1.62428	-1.62433	-1.62432	0.00003	-0.00002	-0.00001	-1.62431
50000	-2.03045	-2.03050	-2.03052	0.00005	0.00000	-0.00002	-2.03050
60000	-2.43667	-2.43674	-2.43677	0.00005	-0.00002	-0.00005	-2.43672
70000	-2.84291	-2.84300	-2.84302	0.00006	-0.00003	-0.00005	-2.84297
80000	-3.24914	-3.24920	-3.24925	0.00006	0.00000	-0.00005	-3.24920
90000	-3.65530	-3.65538	-3.65543	0.00008	0.00000	-0.00005	-3.65538
100000	-4.06136	-4.06149	-4.06152	0.00009	-0.00004	-0.00007	-4.06145

The following polynomial equation, described in ASTM E74-13 has been fitted to the force and deflection values obtained in the calibration using the method of least squares.

response = A0 + A1(load) + A2(load)^2 + A3(load)^3 + A4(load)^4

Where: **A0** 1.26845873E-5
A1 -4.06037323E-5
A2 5.6929943E-14
A3 -5.8162163E-18
A4 4.1538608E-23

load = B0 + B1(response) + B2(response)^2 + B3(response)^3 + B4(response)^4

Where: **B0** 3.11428743E-1
B1 -2.46282820E+4
B2 8.42042379E-1
B3 2.13472887E+0
B4 3.75551770E-1

The following values as defined in ASTM E74-13 were determined from the calibration data.
Lower Limit Factor, LLF 2.471 LBF

Figure 4. ASTME74 data for Morehouse reference standard.

4. 2 Bar Data

Repeatability

To test repeatability on the 2 bar UCM, 10 runs of 10 forces ranging from 10,000 lbf through 100,000 lbf were applied to the unit under test without rotation.

Runs 4 through 7 were used to calculate repeatability.

A per point uncertainty analysis using the Welch-Satterthwaite equation was performed using this data. The Welch–Satterthwaite equation is used to calculate an approximation to the effective degrees of freedom of a linear combination of independent sample variances, also known as the pooled degrees of freedom.

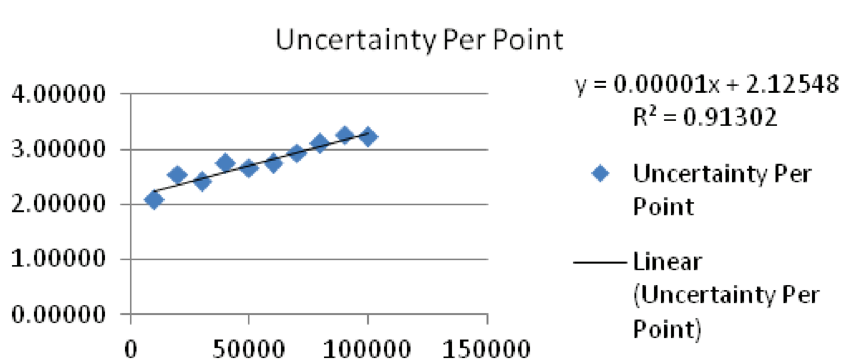
Reproducibility

To test reproducibility on the 2 bar UCM, 6 runs of 6 forces (5,000; 20,000; 40,000; 60,000; 80,000; 100,000 lbf) were applied to the unit under test during a rotational test. The unit under test was rotated 60 degrees on its primary axis between each run.

This data was calculated in accordance with section 8.3 of the ASTM E74-13a titled Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machine. The ASTM Lower Limit Factor for the load cell in the 2 bar Universal Calibrating Machine was 5.332 lbf.

This and the repeatability test was repeated using the 3 bar UCM (Section 5).

Laboratory	Morehouse								
Parameter	FORCE	Range	10K-100K	Sub-Range					
Technician	HZ	Standards Used							
Date	12/21/2015								
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Reproducibility Between Techs		A	Normal	1.000	-1				
Repeatability Between Techs		A	Normal	1.000	0				
Repeatability	466.9004E-3	A	Normal	1.000	3	466.90E-3	218.00E-3	8.15%	15.8E-3
Standard Deviation	1.0296E+0	A	Normal	1.000	200	1.03E+0	1.06E+0	39.64%	5.6E-3
Resolution of UUT	250.0000E-3	B	Resolution	3.464	200	72.17E-3	5.21E-3	0.19%	135.6E-9
Environmental Conditions	1.5000E+0	B	Rectangular	1.732	200	866.03E-3	750.00E-3	28.05%	2.8E-3
Stability of Ref Standard	000.0000E+0	B	Rectangular	1.732	200	000.00E+0	000.00E+0	0.00%	000.0E+0
Ref Standard Resolution	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.03%	3.5E-9
Miscellaneous Error									
Morehouse CMC	1.6000E+0	B	Expanded (95.45% k=2)	2.000		800.00E-3	640.00E-3	23.93%	
			Combined Uncertainty (u_c)=			1.64E+0	2.67E+0	100.00%	24.3E-3
			Effective Degrees of Freedom			294			
			Coverage Factor (k) =			1.97			
			Expanded Uncertainty (U) K =			3.22	0.00322%		
Slope Regression Worksheet									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	100000.00	99999.94	99999.69	99999.69	100000.68	100000	0.4669	0.0016%	1.6
Repeatability (Of Error)			Average Standard Deviation of Runs			0.466900			



Force Point	Expanded UNC
10000	2.09
20000	2.54
30000	2.40
40000	2.74
50000	2.67
60000	2.75
70000	2.94
80000	3.10
90000	3.27
100000	3.22

Figure 5. 2 bar 100K data point example. Expanded uncertainty 3.22 lbf.

5. 3 Bar Data

Repeatability

The identical test method used to test repeatability on the 2 bar UCM was used on the 3 bar UCM. To test repeatability on the 3 bar UCM, 10 runs of 10 forces ranging from 10,000 lbf through 100,000 lbf were applied to the unit under test without rotation.

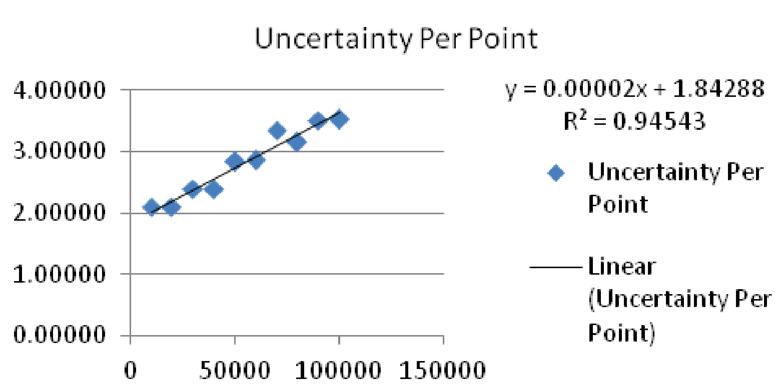
Runs 4 through 7 were used to calculate repeatability.

A per point uncertainty analysis using the Welch-Satterthwaite equation was performed using this data.

Reproducibility

The identical test method used to test reproducibility on the 2 bar UCM was used on the 3 bar UCM. To test reproducibility on the 3 bar UCM, 6 runs of 6 forces (5,000; 20,000; 40,000; 60,000; 80,000; 100,000 lbf) were applied to the unit under test during a rotational test. The unit under test was rotated 60 degrees on its primary axis between each run. This data was calculated in accordance with section 8.3 of the ASTM E74-13a titled Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machine. The ASTM Lower Limit Factor for the load cell in the 3 bar Universal Calibrating Machine was 5.201 lbf.

Measurement Uncertainty Budget Worksheet									
Laboratory	Morehouse								
Parameter	FORCE	Range	10K-100K	Sub-Range					
Technician	HZ	Standards Used							
Date	12/21/2015								
Uncertainty Contributor	Magnitude	Type	Distribution	Divisor	df	Std. Uncert	Variance (Std. Uncert^2)	% Contribution	u^4/df
Reproducibility Between Techs		A	Normal	1.000	-1				
Repeatability Between Techs		A	Normal	1.000	0				
Repeatability	814.9853E-3	A	Normal	1.000	3	814.99E-3	664.20E-3	21.29%	147.1E-3
Standard Deviation	1.0296E+0	A	Normal	1.000	200	1.03E+0	1.06E+0	33.97%	5.6E-3
Resolution of UUT	250.0000E-3	B	Resolution	3.464	200	72.17E-3	5.21E-3	0.17%	135.6E-9
Environmental Conditions	1.5000E+0	B	Rectangular	1.732	200	866.03E-3	750.00E-3	24.04%	2.8E-3
Stability of Ref Standard	000.0000E+0	B	Rectangular	1.732	200	000.00E+0	000.00E+0	0.00%	000.0E+0
Ref Standard Resolution	100.0000E-3	B	Resolution	3.464	200	28.87E-3	833.33E-6	0.03%	3.5E-9
Miscellaneous Error									
Morehouse CMC	1.6000E+0	B	Expanded (95.45% k=2)	2.000		800.00E-3	640.00E-3	20.51%	
			Combined Uncertainty (u_c)=			1.77E+0	3.12E+0	100.00%	155.5E-3
			Effective Degrees of Freedom			62			
			Coverage Factor (k) =			2.00			
			Expanded Uncertainty (U) K =			3.53	0.00353%		
Slope Regression Worksheet									
	Applied	Run 1	Run 2	Run 3	Run 4	Average	Std. Dev.	Ref CMC	LBF
1	100000.00	100000.80	99999.08	100000.55	99999.57	100000	0.8150	0.0016%	1.6
Repeatability (Of Error)			Average Standard Deviation of Runs			0.814985			



Force Point	Expanded UNC
10000	2.10
20000	2.10
30000	2.40
40000	2.40
50000	2.84
60000	2.86
70000	3.36
80000	3.16
90000	3.52
100000	3.53

Figure 6. 3 bar 100K data point example. Expanded uncertainty 3.53 lbf.

FORCE APPLIED	2BAR CMC	%	3BAR CMC	%
10000	2.09	0.0209%	2.10	0.0210%
20000	2.54	0.0127%	2.10	0.0105%
30000	2.40	0.0080%	2.40	0.0080%
40000	2.74	0.0069%	2.40	0.0060%
50000	2.67	0.0053%	2.84	0.0057%
60000	2.75	0.0046%	2.86	0.0048%
70000	2.94	0.0042%	3.36	0.0048%
80000	3.10	0.0039%	3.16	0.0040%
90000	3.27	0.0036%	3.52	0.0039%
100000	3.22	0.0032%	3.53	0.0035%
STDEV	0.37		0.56	
AVG	2.77		2.83	

	2BAR LLF 5.332	2BAR LLF 5.332	3BAR LLF 5.201	3BAR LLF 5.201
FORCE APPLIED	MAX DIFF COUNTS	MAX DIFF LBF	MAX DIFF COUNTS	MAX DIFF COUNTS
5000	5	1.25	1	0.25
20000	15	3.75	11	2.75
40000	15	3.75	18	4.5
60000	24	6	23	5.75
80000	22	5.5	32	8
100000	40	10	37	9.25
STD DEV	12.13	2.69	13.44	3.04
AVG	18.05	5.08	18.17	5.10

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
2 BAR	9	25.62868	2.847631	0.090816
3 BAR	9	26.15768	2.906408	0.275684

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.015547	1	0.015547	0.084839	0.774586	4.493998
Within Groups	2.931997	16	0.18325			
Total	2.947544	17				

Figure 7. Data comparison using analysis of variance.
Note: The CMC % is better than 0.021 % through the Full Range.

6. Key Findings

Key Finding 1

The preliminary results on the 2 bar Universal Calibrating Machine showed better repeatability on 7 of 10 test points. The average calibration and measurement capability was higher on the 3 bar machine and there was more variation in the overall results on the 3 bar machine. On both machines, the Calibration and Measurement Capability (CMC) was 0.210 % or better throughout the full loading range. From 30 % of the measurement range and up, the CMC was better than 0.01 %. Adding a second reference standard of 30,000 lbf capacity, should allow a laboratory to maintain a CMC of better than 0.01 % from 10,000 lbf through 100,000 lbf.

Key Finding 2

The above data was compared using ANOVA analysis. Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences among group means and their associated procedures. ANOVA allows us to know if there is an agreement between the means of several groups. The average of the differences between the ASTM E74 predicted curve values and the individual 6 runs were statistically equivalent. The average difference was less than the resolution of the unit under test.

The ANOVA analysis in this article used a significance level (α) of 0.05. An Alpha of 0.05 indicates that a 5 % risk difference exists to get a sample that is not representative of the population. ANOVA analysis shows a p-value of greater than 0.05. This means we should fail to reject