FLUKE®

Calibration

Guide for the uncertainty analysis in pressure when using P3000 Series Deadweight Testers

Technical Note

2170TN13

The pressure balance is a fundamental instrument designed to precisely regulate and measure pressure. A pressure exerted upward on the area of a floating piston is measured by balancing it with the force of gravity acting downward on a known load of mass. The methods used to determine pressure are thoroughly documented, including in references Dadson, Lewis and Peggs "The Pressure Balance, Theory and Practice"[1], NCSLI's RISP4 "Deadweight Pressure Gauges" [2], EA 10/03 "Calibration of Pressure Balances" (formerly EAL-G26) [3], and OIML's R 110 "Pressure Balances"[4]. These references suffice to describe the use of a pressure balance as long as the pressure balance equation, as defined in each document, is used to calculate pressure.

Some pressure balances, also referred to as deadweight testers (DWT), are designed to be used without the requirement to perform a complex calculation at each pressure value. The need to perform corrections to determine delivered pressure is eliminated in a DWT by assuming values for some of the variables described in the pressure balance equation. Piston and weight set combinations are then manufactured in a manner to account for the assumed values. The result is the pressure measured by the DWT is equal to the sum of the nominal values indicated on the individual weights loaded. The uncertainty when using a DWT in such a fashion is usually greater than when performing a full calculation because of the deviation of the actual measurement conditions from the values assumed at the time of piston and weight set manufacturing.

This technical note is a guide for estimating the measurement uncertainty of Fluke Calibration P3000 series DWTs. Three distinct methods of operating the DWTs are considered. The first method, referred to as "full correction," assumes that variables that significantly affect pressure measurement are quantified and pressure is calculated using the pressure balance equation (referenced above). Another method considered, referred to as "no correction," assumes that pressure is determined strictly by adding the nominal values indicated on the loaded weights. In a third method covered by this document, "partial correction," pressure is determined by compensating the "no correction" value (summation of the nominal weights loaded) with simple piston-cylinder temperature and gravity corrections. The partial correction method is particularly useful if a DWT is being used at gravity different from that for which it was designed; for example, the DWT was never adjusted to the local gravity of the location in which it is used, or a DWT has changed locations. The partial correction method is also useful if the ambient temperature during operation is significantly different from the design temperature.

Fluke Calibration has standardized the instrumental measurement uncertainty specifications for the P3000 line of DWTs so that a product uncertainty specification is available for all three modes of use; full correction, partial correction and no correction. This document explains the influences based on method of use and compiles them into uncertainty budgets (see tables 3 through 6). It is intended to be used as a guide for the justification of the product uncertainty specifications listed in the calibration reports delivered with P3000 DWTs after July 1, 2012. For all DWTs manufactured prior to July 2012, product uncertainty specifications are based on the full correction only as stated in the calibration reports for those DWTs.

Though this technical note presents a great deal of information, it is not necessary to understand all the physics behind the sources of uncertainty. Understanding the influences may be helpful when trying to reduce the uncertainty in pressure, but not completely necessary when using the DWT as delivered. To use this document to determine the instrumental measurement uncertainty, one might do the following:

1. Use the model number on the DWT label to determine which category it falls into from Table 1.
2. Ensure you are within the environmental limits described in section 3.
3. Determine if the DWT has a weight set for each piston-cylinder or if two piston-cylinders share a weight set ("matched").
4. Determine which method you are using: full correction, partial correction, or no correction.
5. Based on the category, configuration (match or no match) and method, identify the appropriate column in the uncertainty tables listed at the end of the document (Tables 3 through 6).
6. Use the number at the bottom of the column titled Final Expanded Uncertainty at K=2, Maximum of % of reading or % of FS.
7. If this uncertainty is acceptable, there is no need for further analysis. This is the standard uncertainty delivered with your equipment and will be reflected in the calibration report. Note that the instrumental measurement uncertainty in the calibration report may be slightly higher to normalize the published value. If you wish to improve from standard uncertainty, each applicable component of uncertainty described in section 5 should be analyzed for opportunities.

2. Scope

The scope of this document is Fluke Calibration P3000 Deadweight Testers manufactured on or after July 1, 2012. There are many models in the P3000 product line, so for the purpose of this uncertainty analysis they are categorized as shown in table 1.

Table 1. Categories of P3000 models

	Category	Range	Model*
1	Vacuum	-3 to -100 kPa (-30 to -1000 mbar, -1 to -30 InHg)	P3011, P3022 (VAC), P3023 (VAC), P3024 (VAC)
2	Low Pressure Gas	Positive gauge ranges up to 200 kPa (up to 30 psi)	P3012, P3013, P3023 (HP)
3	Medium Pressure Gas	1000 and 3500 kPa (150 and 500 psi)	P3014, P3015, P3024 (HP)
4	High Pressure Gas	7000 and 14000 kPa (1000 and 2000 psi)	P3031, P3032
5	Low Pressure Oil	3.5 and 14 MPa (500 and 2000 psi)	P3111, P3112, P3123(LP), P3124(LP), P3125(LP)
6	Medium Pressure Oil	35 and 70 MPa (5000 and 10000 psi)	P3113, P3114, P3123(HP), P3124(HP)
7	High Pressure Oil	110 MPa and 140 (16000 and 20000 psi)	P3115, P3116, P3125(HP)
8	Very High Pressure Oil	200, 260 and 400 MPa (30000, 40000 and 60000 psi)	P3830, P3840, P3860
9	Low Pressure Water	3.5 MPa (500 psi)	P3211, P3223(LP), P3224(LP)
10	Medium Pressure Water	35 and 70 MPa (5000 and 10000 psi)	P3213, P3214, P3223(HP), P3224(HP)

* Full model names include variations depending on the nominal unit of measurement and inclusion of a built-in pressure pump.

3. Environmental limits

In order to put bounds on the uncertainties, it is necessary to define the environmental limits with which the DWT is intended to be used. For situations where the DWT is used outside of the defined environmental limits, specifically temperature and change in temperature, this document provides some guidance on how to expand the uncertainty budget to account for additional uncertainties associated with the expanded environmental limits.

Environmental limits

Ambient temperature: 18 to 28˚C (64 to 82˚F) with air conditioning variations not more than ±1 ˚C (± 1.8 ˚F) and average variations no more than 1 ˚C (± 1.8 ˚F) per hour

Ambient pressure: 80 to 105 kPa (11.6 to 15.2 psi, 23.6 to 31 inHg)

Ambient humidity: non-condensing

Location: Assumes no change in location where gravity was determined

Air drafts: Assumes no significant air drafts

4. Levels of use

This technical note presents analysis for pressure determination using three different methods; full correction, partial correction and no correction. For all levels of use, the uncertainties described here assume that the DWT is in the proper working condition. For proper operation, the piston-cylinder must be clean and in free float, the weights must be rotating, and the fall rate sufficiently low. There can also be no significant leaks or restrictions that would cause differential pressures in the pressure circuit between the floating piston and the device being tested. To realize the stated uncertainties, the DWT must also be used within the environmental limits shown in section 3.

4.1 Full correction

The full correction method is based on the pressure balance equation for gauge mode only and typically requires software. It applies to both negative and positive gauge pressure measurements. The equation for full correction is defined as:

$$\frac{M \times g_l \times \left(1 - {}^{\rho(air)}\!/_{\rho\_(mass)}\right) + \pi DT}{A_{(23,0)} \times [1 + (\alpha_p + \alpha_c) \times (\theta - 23)] \times (1 + \lambda P)} - (\rho_{(fluid)} - \rho_{(air)}) \times g_l \times h$$

where:

M = Total true mass load ....[kg]
gl = Local acceleration due to gravity ....[m/s^2]
ρ(air) = Ambient air density ....[kg/m^3]
ρ(mass) = Average density of mass load ....[kg/m^3]
T = Surface tension (considered 0 with gas) ......[N/m]
D = Diameter of the piston ....[m]
ρ(fluid) = Density of the test medium (gas or oil)..........[kg/m^3]
h = Difference in height between DWT reference level and test reference level ....[m]
A(23,0) = Piston-cylinder effective area at 23 ˚C and 0 pressure ....[m^2]
αp = Linear thermal expansion coefficient of piston ....[$˚C^{-1}$]
αc = Linear thermal expansion coefficient of cylinder ....[$˚C^{-1}$]
θ = Temperature of the piston-cylinder...............[˚C]
λ = Elastic deformation coefficient of the piston-cylinder ....[Pa^{-1}]
P = Pressure applied to the piston-cylinder........[Pa]

Calculating pressure this way completely eliminates any dependency on the nominal pressure values engraved on the DWT weights. Note that Fluke Calibration offers several software packages, including PressCal, COMPASS® for Pressure and WinPrompt, which calculate pressure using the full correction method.

5. Uncertainties

In this section the influences of uncertainty are analyzed to support the values presented in Tables 3-6. The effect of each influence is described as it applies to all three levels of use, and values for each are presented in the final uncertainty budget (Section 7).

The uncertainties are determined either as a percent of reading, a fixed value of pressure, or a combination of both. The final uncertainty tables are formatted with relative uncertainties (top) and fixed uncertainties (bottom) reported and combined separately. The fixed uncertainties are converted to a percentage of full scale to relate to the uncertainty specifications given. All uncertainties are calculated and presented following the recommendations of "Guide to the Expression of Uncertainty in Measurement" [5].

5.1 Mass

There are two uncertainties for mass considered. The full correction level of use relies solely upon the uncertainty in the measurement of the masses as they are listed in the calibration report. This uncertainty is to be within ±0.002% or 2 mg, whichever is greater at k=2. When using these mass values to determine pressure using the full correction method, it is expected that the non-nominal values reported in the calibration report are added up with the resolution shown.

For the partial or no correction, an additional uncertainty is considered to account for the deviation of the actual adjusted mass value from the target mass value for each weight. This mass adjustment allowance uncertainty is ±0.005% or 5 mg, whichever is greater at k=3. The coverage factor of 3 is used because a mass will be rejected or adjusted if found outside specification, so there is little probability of exceeding adjustment allowance. Only in the cases of the vacuum and low pressure gas range is the 5 mg fixed uncertainty significant, and therefore included in the final uncertainty tables for partial and no correction levels.

5.2 Gravity

The contribution from uncertainty of gravity is the same for all levels of use. The value of local gravity is either entered by the user into the pressure balance equation for full correction, included in the local gravity correction for partial correction, or is used to determine adjusted mass values when the DWT is adjusted for local gravity for the no correction level of use. Uncertainty contribution from differences of local gravity when the DWT is used in multiple locations is not considered, because there are no reasonable bounds. The error can be very significant with respect to the overall target uncertainties. For example, the approximate acceleration of gravity in Helsinki and Mexico City is 9.819 and 9.779 m/s2 respectively. This difference translates directly into an apparent pressure measurement discrepancy of approximately 0.4% if the same device is used in these two locations without mathematical correction.

Local gravity is known or can be readily determined with low uncertainty in most parts of the world in which a DWT would typically be used. Uncertainty from the value of local gravity of ±0.002% at k=2 is used for this uncertainty analysis because it can be reasonably achieved.

5.3 Effective area

The effective area of each piston-cylinder supplied with the P3000 DWT is determined from a sufficiently low point in its range to the full scale of that range. The uncertainties reported in tables 3-6 account for all influences during the test to determine the effective area and are a worse case value for the entire range. The uncertainty includes the deformation of the piston-cylinder throughout its range and applies to all methods of use.

5.4 Piston-cylinder temperature

The materials of a piston and cylinder expand and contract with increase and decrease in temperature respectively. To compensate for the corresponding change of effective area, temperature of the piston-cylinder must be known. Studies indicate that when the P3000 DWT is operated within the stated environmental limits it is sufficient to estimate the piston-cylinder temperature as equal to the ambient temperature near the DWT. When monitoring temperature in this manner, the uncertainty contribution from piston-cylinder temperature is dependent upon the uncertainty in the temperature measuring device, an allowance for variance from the assumption that the temperature measured is equal to the temperature of the piston-cylinder and the uncertainty of the thermal expansion coefficient of the material of the piston-cylinder.

Appendix A shows a study of the uncertainty contribution from the assumption that the ambient air near the DWT is equal to the actual piston-cylinder temperature. Coupled with an uncertainty in measured temperature of ±1 °C (±1.8 °F) at k=2 for the thermometer, it is reasonable to assume an uncertainty in piston-cylinder temperature of ±2 °C (±3.6 °F) at k=2. The values reported for full correction and partial correction (tables 3 and 4) reflect the contribution from uncertainty of piston-cylinder temperature measurement at k=2, including uncertainty of the thermal expansion coefficient. In the level of use in which no corrections are made, the uncertainty in temperature is defined as the deviation specified by the operating temperature limits from the design temperature of 23 ˚C. Tables 5 and 6 shows these uncertainties at k=1, including uncertainty of the thermal expansion coefficient.

5.5 Piston-cylinder deformation

The pressure applied to a DWT causes elastic deformation of the piston and cylinder, resulting in an increased effective area with increased pressure. Uncertainty of elastic deformation is already considered in the determination of effective area (refer to Section 5.3). The partial or no correction methods do not account for changes in effective area with changes in pressure except for the initial mid-scale pressure entered into the design variables (see section 4.2). Because of this an uncertainty must be included that accounts for the deformation that is not being accounted for.

For DWTs with ranges that are equal to or greater than 20,000 psi, the main mass target values are adjusted to account for changes in effective area due to pressure deformation. This greatly reduces this uncertainty, but main masses must be used sequentially.

5.6 Dual range match

The P3000 line offers some models that feature dual piston-cylinders to achieve a very wide pressure range in a single instrument. The P312x and P322x (oil and water medium respectively) dual piston models come standard with a single shared weight set. To facilitate a shared weight set, the deviations of the piston-cylinder effective areas from nominal are matched to within 0.015% of each other. Each weight is then trimmed to a mass value between the ideal compensated values for the two pistons, with more consideration given to the higher pressure range. The matching process ultimately contributes a worse case uncertainty of ±0.007% at k=2 for the low range, and ±0.003% at k=2 for the high range.

Note: ***The uncertainties described in 5.1 (manufactured mass), 5.5 and 5.6, that apply to partial or no correction levels, are based on limits and are worst case. The user of the DWT can evaluate these uncertainties as a whole using the calculated pressure tables at the end of the calibration report.***

Figure 1. Example of the results of a model P3124-3 matched piston set.

Calculated Pressure List For High Range Piston-Cylinder

Nominal Pressure [psi]	Calc Pressure [psi]	Weight Combination	Calc-Nominal [% of reading]
200	200.019	P, B	0.010%
2000	2000.185	P, B, 5, 6, 7, 8, 9	0.009%
4000	4000.291	P, B, 1, 5, 6, 7, 8, 9	0.007%
6000	6000.306	P, B, 1, 2, 5, 6, 7, 8, 9	0.005%
8000	8000.142	P, B, 1, 2, 3, 5, 6, 7, 8, 9	0.002%
10000	9999.90	P, B, 1, 2, 3, 4, 5, 6, 7, 8, 9	-0.001%

Calculated Pressure List For Low Range Piston-Cylinder

Nominal Pressure [psi]	Calc Pressure [psi]	Weight Combination	Calc-Nominal [% of reading]
10	9.9995	P, A	-0.005%
100	99.9964	P, A, 5, 6, 7, 8, 9	-0.004%
200	199.9921	P, A, 1, 5, 6, 7, 8, 9	-0.004%
300	299.9867	P, A, 1, 2, 5, 6, 7, 8, 9	-0.004%
400	399.9757	P, A, 1, 2, 3, 5, 6, 7, 8, 9	-0.006%
500	499.9643	P, A, 1, 2, 3, 4, 5, 6, 7, 8, 9	-0.007%

Figure 1 shows the results of a matched set. The calculated pressure has an uncertainty that is described in the final fully corrected table. The uncertainty of a partially corrected matched low pressure oil (bottom table in figure 1) is ±(maximum of 0.013% rdg or 0.0008% FS) and medium pressure oil (top table in figure 1) is ±(maximum of 0.012% rdg or 0.0005% FS). It is easy to see that the high side is biased towards the positive and the low side is biased toward the negative, due to a match of 0.015%. If not making a full correction, it is perfectly acceptable to use the deviations shown in figure 1 as one uncertainty to replace the three uncertainties described in 5.1, 5.5 and 5.6.

5.7 Air buoyancy

A buoyant force, equal to the weight of the air displaced by the volume of the piston and loaded mass, is exerted upwards on the floating DWT piston. The pressure balance equation includes a component for compensation of the air buoyancy effect.

All masses are calibrated to an apparent mass of 7920 kg/m^3. Although no hardware is supplied with P3000 models to do so, it is reasonable to assume that the ambient conditions can be determined within ±1 ˚C (±1.8 ˚F), ±2 kPa (±0.6 inHg) and ±50 % RH. Air density can then be calculated to within ±0.025 kg/m^3 resulting in a total uncertainty contribution ±0.0005% at k=2 from the air buoyancy correction.

In the case of partial or no correction, P3000 DWT weights are manufactured to target mass values assuming a nominal air density of 1.2 kg/m^3. Within the stated P3000 DWT environmental limits (referenced in section 3), air density can range from 1.25 to 0.91 kg/m^3, resulting in a range of air buoyancy correction from 0.016% to 0.012%. The difference between 1.2 kg/m^3 and the lower limit of 0.91 kg/m^3 results in a maximum uncertainty contribution of ±0.0036% at k=2.

5.8 Level

The pressure balance equation assumes that all balanced forces are aligned vertically with the force of gravity. The verticality of the piston is accomplished using a target level on the base that is matched to the piston-cylinder mounting posts. The acceptable tolerance of verticality is 20 minutes of a degree from vertical for vacuum, low pressure oil and water ranges, and 10 minutes of a degree for all other ranges. Though level error is normally described as an asymmetrical distribution, for the sake of simplicity the uncertainty contribution is given as ±0.0015% and ±0.0005% respectively at k=2.

5.9 Performance

The P3000 DWT performance uncertainty is used to describe a combination of uncertainty sources, including:

- Sensitivity: Minimum amount of mass to create a measurable change in output
- Straightness: Consistency of the effective area along the mated surface (changes in effective area with float position of the piston)
- Rotation: Changes in output due to changes in rotation speeds or direction

The performance specification is determined for each piston-cylinder model and range through empirical analysis of P3000 manufacturing and installed base data. Each new piston is manufactured and tested to meet specified performance tolerances. Table 2 reflects the combined performance uncertainty for each range at k=2.

5.10 Stability

P3000 DWTs are designed to be very stable. A properly maintained instrument will provide highly reproducible measurements over time. The uncertainty contribution of one-year stability, including the effective area of the piston-cylinder and mass values of the weights, can be conservatively budgeted as ±0.001% at k=2. Stability is traditionally considered a rectangular distribution and is treated as such in the final uncertainty tables.

5.11 Head height, surface tension and fluid buoyancy

5.11.1 Head height

The pressure balance equation includes a term to correct for the pressure generated by the height of the test medium fluid column between the pressure balance and the device under test.

The height of the fluid column is measured from the reference level of the pressure balance to the

Table 2. Uncertainties due to performance at k=2

	Vac	Low Press Gas	Med Press Gas	High Press Gas	Low Press Oil	Med Press Oil	High Press Oil	Very High Press Oil	Low Press Water	Med Press Water
	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]
Sens.	0.0005	0.0005	0.0005	0.0010	0.0010	0.0010	0.0010	0.0015	0.0015	0.0015
Stra.	0.0020	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030
Rot.	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Comb	**0.0025**	**0.0034**	**0.0034**	**0.0035**	**0.0035**	**0.0035**	**0.0035**	**0.0037**	**0.0037**	**0.0037**
	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]
Sens.	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0001	0.0001	0.0004	0.0003
Rot.	0.0002	0.0002	0.0002	0.0005	0.0005	0.0005	0.0003	0.0002	0.0005	0.0005
Comb	**0.0003**	**0.0003**	**0.0003**	**0.0005**	**0.0006**	**0.0005**	**0.0003**	**0.0002**	**0.0006**	**0.0006**

reference level of the device under test, which is a negative value if the device under test is positioned lower than the pressure balance. The reference level when using the pressure balance equation is considered to be the bottom of the piston for most ranges, or the top of the piston for vacuum ranges.

To simplify operation when using a P3000 DWT with partial or no correction, the reference level is established as the top of the test port seal. This change in reference level is accomplished by adjusting the mass of the weight carrier of hydraulic DWTs to account for the difference in height between the reference level of the piston and the test port seal. The correction is insignificant for DWTs using gas as the medium.

5.11.2 Surface tension

When using a DWT with a liquid medium or liquid lubrication, the medium applies a downward force along the circumference of the piston. A term in the pressure balance equation corrects for this "surface tension" force around the circumference of the piston.

When using a P3000 DWT with partial or no correction, correction for surface tension is accomplished by adjusting the mass of the weight carrier.

5.11.3 Test fluid buoyancy

If a piston is perfectly cylindrical, the bottom of the piston can be considered to be the reference level of the pressure balance, and no correction is required for the buoyant force on the piston immersed in the test medium. However, many DWT pistons feature irregular shapes, such as a stop to retain the piston when the maximum float position is exceeded. An upward buoyant force is generated equal to the weight of the fluid displaced by the irregular feature. The buoyant force can be calculated and corrected for separately, but is usually compensated for by an offsetting adjustment in the reference level or mass of the piston.

For P3000 DWT partial and no correction methods, fluid buoyancy compensation is accomplished with a mass correction to the weight carrier.

5.11.4 Accounting for head height, surface tension and fluid buoyancy for the full correction method

Some software packages explicitly call out reference level offset, surface tension and fluid buoyancy corrections. If the software does not explicitly make these corrections, any or all of them may be accounted for through respective mass value corrections.

The calibration report for a hydraulic DWT will give the corrections in terms of mass, to allow for those corrections to be made by adjusting the piston mass entered into the software. Any or all of the corrections may be applied in this manner. Figure 2 is an example of a calibration report for a dual range DWT. If the software did not account for any of these corrections the piston mass value could be changed as follows for the high range in Figure 2:

Corrected piston mass = 0.0212863 kg + 0.0000203 kg - 0.0002743 kg + 0.0000634 kg = 0.0210957 kg

Care should be taken in making the correction this way, because the software may be making the correction already.

Figure 2. Example data for a dual range DWT

	High Range P-C	Low Range P-C	Unit
SN:			
Effective Area (23,0) :	4.03444E-06	8.06938E-05	m^2
Effective Area Unc:	48.3	43.6	ppm
Elastic Deformation:	1.03E-06	5.52E-06	MPa^{-1}
Thermal Expansion:	1.10E-05	1.66E-05	$°C^{-1}$
Piston Mass:	0.0212863	0.0988276	kg
Piston Mass Unc:	0.0000004	0.0000002	kg
Surface Tension:	0.0000203	0.0000909	kg
Fluid Buoyancy:	-0.0002743	-0.0003340	kg
Head Correction:	0.0000634	-0.0051659	kg

5.11.5 Uncertainty

Uncertainty contributions for head correction, surface tension effect and buoyancy of the piston in the test medium are combined and reported as a single value in Tables 3-6. The corrections are constant values, so uncertainty contributions are presented in terms of percent of full scale. There is not an additional uncertainty for head corrections made from the test port seal to other reference levels. The uncertainty in head height assumes the piston is in its mid-float position. With a correction of about 0.013 psi per cm, variances in this uncertainty can be calculated for different ranges when not at mid-float.

The combined effect is insignificant for low pressure gas, medium pressure gas and vacuum ranges, because the gas medium has very low density and no surface tension. A significant effect is associated with high pressure gas P3000 models because the piston is immersed in a liquid lubricant, with the gas test medium directly acting upon the liquid lubricant in a reservoir. In addition to head correction, surface tension and fluid buoyancy, there is uncertainty associated with the level of the liquid lubricant in the reservoir.

6. References

1. R.S. Dadson, S.L. Lewis and G.N. Peggs, The Pressure Balance, Theory and Practice, NPL Department of Industry, 1992
2. NCSLI's RISP4, Deadweight Pressure Gauges, Recommended Intrinsic/Derived Standard Practice, July 1998
3. EA 10/03, Calibration of Pressure Balances (formerly EAL-G26), EUROMET, July 1997
4. OIML R 110, Pressure Balances, 1994
5. Guide to the Expression of Uncertainty in Measurement, JCMP 100:2008.

7. Final uncertainty tables

Tables 3-6 compile the uncertainty contributions described in Section 5. A separate table is presented for each level of use; full correction, partial correction and no correction. Table 6 compiles uncertainty for the special case of oil and water models with dual pistons sharing a single weight set (P312x and P322x). The Fluke Calibration instrumental measurement uncertainty specification is based on either the full correction or no correction (matched piston-cylinder as worst case); however, the values are increased slightly in some cases to achieve a nominal specification for each method of use.

As of July 2012, calibration reports for P3000 DWTs using the full correction method (improved accuracy) reflect:

±(Maximum of, 0.008% of reading or 0.0004% of range) for high and medium hydraulic ranges

±(Maximum of, 0.008% of reading or 0.0008% of range) for low hydraulic ranges and all gas ranges

±(Maximum of, 0.015% of reading or 0.00075% of range) for very high pressure oil

And for P3000 DWTs using no correction, matched or not matched, reflect:

±(Maximum of, 0.015% of reading or 0.00075% of range) for high and medium hydraulic ranges

±(Maximum of, 0.015% of reading or 0.0015% of range) for low hydraulic ranges and all gas ranges

±(Maximum of, 0.02% of reading or 0.001% of range) for very high pressure oil

Uncertainty using the full correction method is typically consistent from one P3000 DWT to another, because variances in piston characteristics and mass adjustments are corrected for mathematically. Uncertainties compiled for the partial and no correction methods are based on worst case, uncorrected variances. Actual performance may be significantly better than the worst case uncertainty reported. If improved uncertainty is desired, a detailed analysis should be performed for the individual DWT.

Table 3. Full correction

	Vacuum	Low Pressure Gas	Medium Pressure Gas	High Pressure Gas	Low Pressure Oil	Medium Pressure Oil	High Pressure Oil	Very High Pressure Oil	Low Pressure Water	Medium Pressure Water
Uncertainty: section	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]
Mass: 5.1	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Gravity: 5.2	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Effective area: 5.3	0.0025	0.0025	0.0029	0.0029	0.0018	0.0021	0.0025	0.0073	0.0018	0.0025
Piston-cylinder Temperature: 5.4	0.0012	0.0012	0.0009	0.0009	0.0009	0.0006	0.0006	0.0006	0.0009	0.0006
Air Buoyancy: 5.7	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Level: 5.8	0.0008	0.0003	0.0003	0.0003	0.0008	0.0003	0.0003	0.0003	0.0008	0.0003
Performance: 5.9	0.0013	0.0017	0.0017	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Stability: 5.10	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Combined % Reading	0.0035	0.0036	0.0038	0.0038	0.0032	0.0032	0.0035	0.0077	0.0032	0.0035
Uncertainty: section	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]
Head Height, Surface Tension & Fluid Bouyancy: 5.11	0.00000	0.00000	0.00000	0.00030	0.00029	0.00002	0.00001	0.00000	0.00029	0.00007
Performance: 5.9	0.00014	0.00014	0.00014	0.00027	0.00029	0.00027	0.00016	0.00011	0.00032	0.00029
Combined % Full Scale	0.00014	0.00014	0.00014	0.00040	0.00041	0.00027	0.00016	0.00011	0.00043	0.00030
	Final Expanded Uncertainty at K=2, Maximum of % of reading or % of FS									
	0.007% rdg or 0.0003%FS	0.007% rdg or 0.0003%FS	0.008% rdg or 0.0003%FS	0.008% rdg or 0.0008%FS	0.006% rdg or 0.0008%FS	0.006% rdg or 0.0005%FS	0.007% rdg or 0.0003%FS	0.015% rdg or 0.0002%FS	0.006% rdg or 0.0009%FS	0.007% rdg or 0.0006%FS

Table 4. Partial correction

	Vacuum	Low Pressure Gas	Medium Pressure Gas	High Pressure Gas	Low Pressure Oil	Medium Pressure Oil	High Pressure Oil	Very High Pressure Oil	Low Pressure Water	Medium Pressure Water
Uncertainty: section	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]
Mass: 5.1	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Nominal Mass: 5.1	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
Gravity: 5.2	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Effective area: 5.3	0.0025	0.0025	0.0029	0.0029	0.0018	0.0021	0.0025	0.0073	0.0018	0.0025
Piston-cylinder Temperature: 5.4	0.0012	0.0012	0.0009	0.0009	0.0009	0.0006	0.0006	0.0006	0.0009	0.0006
Piston-cylinder Deformation: 5.5	0.0000	0.0000	0.0005	0.0022	0.0011	0.0029	0.0050	0.0007	0.0011	0.0029
Air Buoyancy: 5.7	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Level: 5.8	0.0008	0.0003	0.0003	0.0003	0.0008	0.0003	0.0003	0.0003	0.0008	0.0003
Performance: 5.9	0.0013	0.0017	0.0017	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Stability: 5.10	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Combined % Reading	0.0043	0.0043	0.0046	0.0051	0.0041	0.0050	0.0065	0.0081	0.0042	0.0052
Uncertainty: section	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]
Head Height, Surface Tension & Fluid Bouyancy: 5.11	0.00000	0.00000	0.00000	0.00030	0.00029	0.00002	0.00001	0.00000	0.00029	0.00007
Performance: 5.9	0.00014	0.00014	0.00014	0.00027	0.00029	0.00027	0.00016	0.00011	0.00032	0.00029
Mass: 5.1	0.00030	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Combined % Full Scale	0.00034	0.00021	0.00014	0.00040	0.00041	0.00027	0.00016	0.00011	0.00043	0.00030
	Final Expanded Uncertainty at K=2, Maximum of % of reading or % of FS									
	0.009% rdg or 0.0007%FS	0.009% rdg or 0.0004%FS	0.009% rdg or 0.0003%FS	0.010% rdg or 0.0008%FS	0.008% rdg or 0.0008%FS	0.010% rdg or 0.0005%FS	0.013% rdg or 0.0003%FS	0.016% rdg or 0.0002%FS	0.008% rdg or 0.0009%FS	0.010% rdg or 0.0006%FS

Table 5. No correction

	Vacuum	Low Pressure Gas	Medium Pressure Gas	High Pressure Gas	Low Pressure Oil	Medium Pressure Oil	High Pressure Oil	Very High Pressure Oil	Low Pressure Water	Medium Pressure Water
Uncertainty: section	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]
Mass: 5.1	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Nominal Mass: 5.1	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
Gravity: 5.2	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Effective area: 5.3	0.0025	0.0025	0.0029	0.0029	0.0018	0.0021	0.0025	0.0073	0.0018	0.0025
Piston-cylinder Temperature: 5.4	0.0054	0.0054	0.0042	0.0042	0.0042	0.0028	0.0028	0.0028	0.0042	0.0028
Piston-cylinder Deformation: 5.5	0.0000	0.0000	0.0005	0.0022	0.0011	0.0029	0.0050	0.0007	0.0011	0.0029
Air Buoyancy: 5.7	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Level: 5.8	0.0008	0.0008	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0008	0.0003
Performance: 5.9	0.0013	0.0017	0.0017	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Stability: 5.10	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Combined % Reading	0.0068	0.0069	0.0061	0.0065	0.0058	0.0057	0.0071	0.0085	0.0058	0.0058
Uncertainty: section	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]
Head Height, Surface Tension & Fluid Bouyancy: 5.11	0.00000	0.00000	0.00000	0.00030	0.00029	0.00002	0.00001	0.00000	0.00029	0.00007
Performance: 5.9	0.00014	0.00014	0.00014	0.00027	0.00029	0.00027	0.00016	0.00011	0.00032	0.00029
Mass: 5.1	0.00030	0.00015	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Combined % Full Scale	0.00034	0.00021	0.00014	0.00040	0.00041	0.00027	0.00016	0.00011	0.00043	0.00030
	Final Expanded Uncertainty at K=2, Maximum of % of reading or % of FS									
	0.014% rdg or 0.0007%FS	0.014% rdg or 0.0004%FS	0.012% rdg or 0.0003%FS	0.013% rdg or 0.0008%FS	0.012% rdg or 0.0008%FS	0.011% rdg or 0.0005%FS	0.014% rdg or 0.0003%FS	0.017% rdg or 0.0002%FS	0.012% rdg or 0.0009%FS	0.012% rdg or 0.0006%FS

Table 6. Matched ranges, partial and no correction

	Partial Correction Matched Range					No Correction Matched Range				
	Low Pressure Oil	Medium Pressure Oil	High Pressure Oil	Low Pressure Water	Medium Pressure Water	Low Pressure Oil	Medium Pressure Oil	High Pressure Oil	Low Pressure Water	Medium Pressure Water
Uncertainty: section	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]	[% rdg]
Mass: 5.1	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Nominal Mass: 5.1	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
Gravity: 5.2	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Effective area: 5.3	0.0018	0.0021	0.0025	0.0018	0.0025	0.0018	0.0021	0.0025	0.0018	0.0025
Piston-cylinder Temperature: 5.4	0.0009	0.0006	0.0006	0.0009	0.0006	0.0042	0.0028	0.0028	0.0042	0.0028
Piston-cylinder Deformation: 5.5	0.0011	0.0029	0.0050	0.0011	0.0029	0.0011	0.0029	0.0050	0.0011	0.0029
Dual Range Match: 5.6	0.0050	0.0025	0.0025	0.0050	0.0025	0.0050	0.0025	0.0025	0.0050	0.0025
Air Buoyancy: 5.7	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Level: 5.8	0.0008	0.0003	0.0003	0.0008	0.0003	0.0003	0.0003	0.0003	0.0008	0.0003
Performance: 5.9	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Stability: 5.10	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Combined % Reading	0.0065	0.0056	0.0070	0.0065	0.0057	0.0076	0.0062	0.0075	0.0077	0.0063
Uncertainty: section	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]	[% FS]
Head Height, Surface Tension & Fluid Bouyancy: 5.11	0.00029	0.00002	0.00001	0.00029	0.00007	0.00029	0.00002	0.00001	0.00029	0.00007
Performance: 5.9	0.00029	0.00027	0.00016	0.00032	0.00029	0.00029	0.00027	0.00016	0.00032	0.00029
Combined % Full Scale	0.00041	0.00027	0.00016	0.00043	0.00030	0.00041	0.00027	0.00016	0.00043	0.00030
	Final Expanded Uncertainty at K=2, Maximum of % of reading or % of FS									
	0.013% rdg or 0.0008%FS	0.011% rdg or 0.0005%FS	0.014% rdg or 0.0003%FS	0.013% rdg or 0.0009%FS	0.011% rdg or 0.0006%FS	0.015% rdg or 0.0008%FS	0.012% rdg or 0.0005%FS	0.015% rdg or 0.0003%FS	0.015% rdg or 0.0009%FS	0.013% rdg or 0.0006%FS

Appendix A. Piston-cylinder temperature study

Section 5.4 considers the uncertainty in measurement of the piston-cylinder temperature. It is assumed that the temperature of the piston-cylinder can be estimated as equal to the temperature of the ambient air near the DWT. To validate this assumption, a simple study has been performed.

The goal of the study was to address three questions:

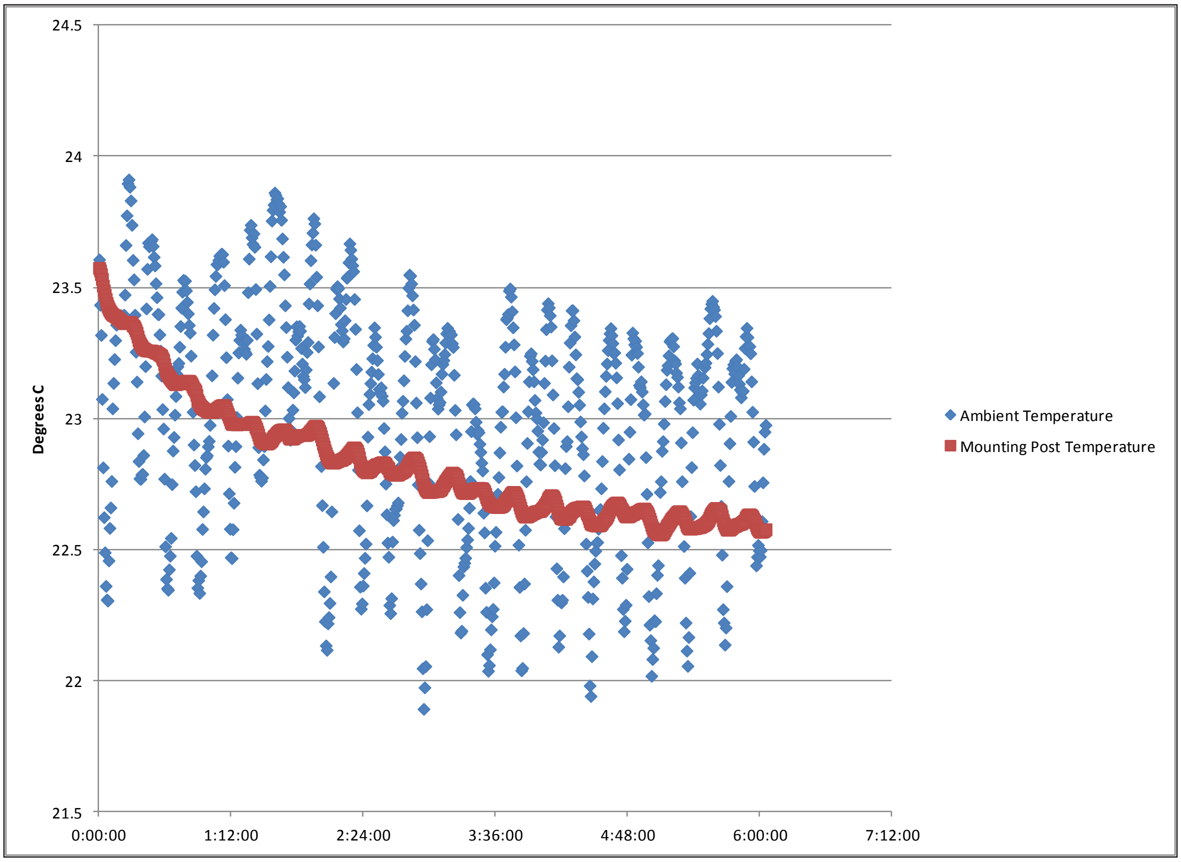
- In a normal air conditioned environment, how much error is there due to the difference in temperature of the surrounding air and the piston-cylinder temperature?
- What effect would a large temperature ramp have on the relation between air temperature and piston-cylinder temperatures?
- What effect can be expected from heating resulting from increase in test pressure?

The tests included a P3123-3 Hydraulic Deadweight Tester, an extra mounting post from the same model of DWT, a Fluke Calibration 1524 Reference Thermometer/5610 Secondary Reference Temperature Probe, a Fluke Calibration 1620A “DewK” Thermo-Hygrometer and a Fluke Ti32 Thermal Imager.

To address the first assumption, a test was performed in which the ambient temperature was recorded for approximately six hours using the Dewk. The ambient temperature sensor was placed on the DWT top surface. To simulate the temperature of the piston-cylinder, the 1524/5610 thermistor probe with an ID very close to the inside diameter of the mounting post was placed in the mounting post and temperature was recorded simultaneously. Figure A1 summarizes the results of the six-hour temperature test.

The uncertainties of the measurements made were approximately ±0.02 ˚C for the mounting post temperature and ±0.25 ˚C for the ambient temperature. The temperature of the mounting post tracked closely to the approximate average of the ambient temperature. The fluctuations of ambient temperature were on the order of ±1 ˚C as the air conditioner cycled throughout the six hours.

Figure A1. Chart of the difference in ambient and mounting post temperature in a controlled air conditioned environment



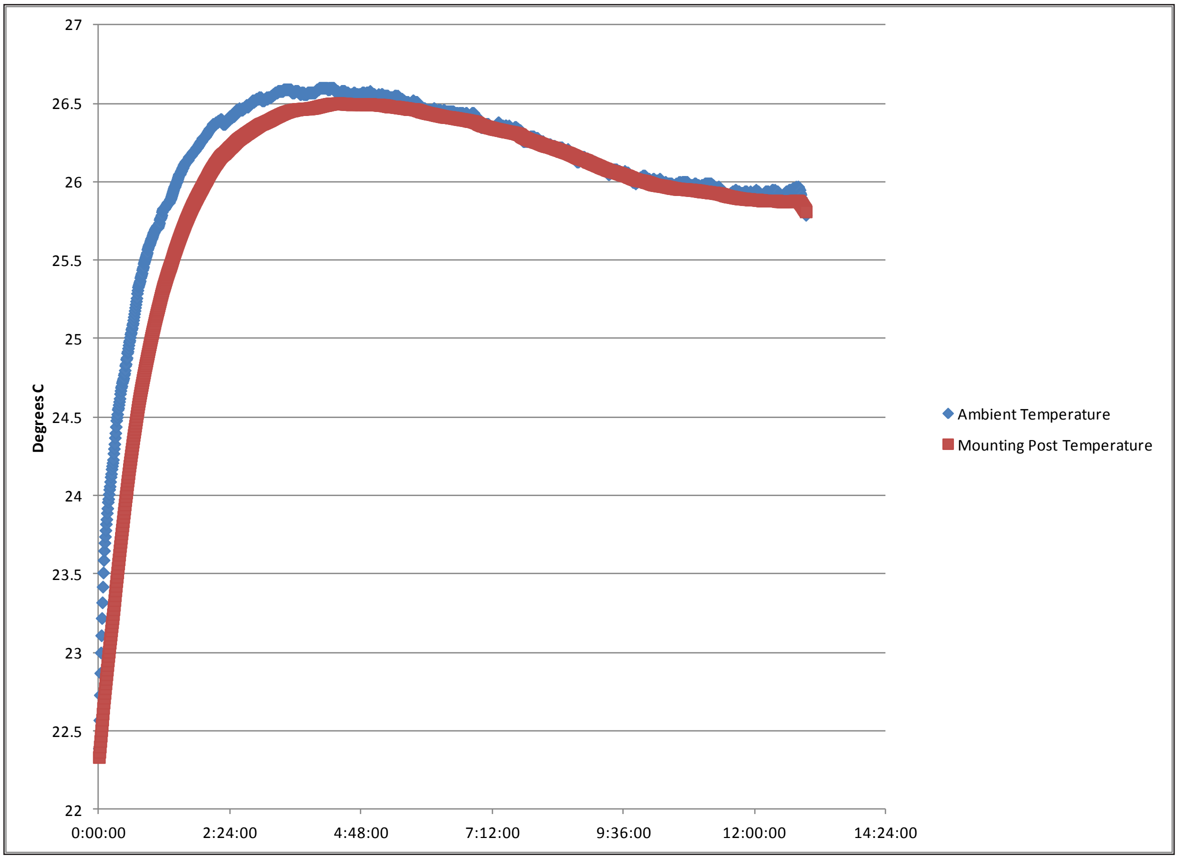
The same DWT and temperature measuring instrument configuration was tested in a temperature-controlled environment. Ambient temperature was decreased to a low temperature and stabilized. Temperature control was then halted and allowed to normalize overnight. Figure A2 summarizes the difference between the ambient and mounting post temperatures as the temperature drifted during this test. The maximum difference between ambient and piston-cylinder temperatures was approximately 1 °C during a ramp of approximately 2.5 °C per hour. Once the temperature stabilized, there was very little difference in the temperatures.

The goal of the final test was to determine the influence from heat exchange due to large increases or decreases in pressure. Key components of the DWT were coated, including the extra mounting post, and a thermal imager was used to monitor changes in temperature during a large pressure excursion. Figure A3 shows a collage of pictures taken with the thermal imager (the first picture a normal one). In each picture taken by the thermal imager. the temperature was stabilized at zero gauge pressure, then the pressure was rapidly increased by 35 MPa (5,000 psi). After a couple seconds, the thermal imager target was placed on a pre-defined location. The pressure was released and the temperature was allowed to stabilize. This test was repeated for several targets. The locations targeted were the head of the piston, the upper part of the high pressure mounting post, the lower part of the high pressure mounting post, the low range mounting post (which sees the same pressure) and the extra mounting post that was used in the earlier tests.

The thermal imaging study analyzed temperature differences between components of the pressurized DWT and the unpressurized control specimen. Due to the substantial thermal inertia of the mounting posts and the fact that the internal volumes of the DWT are relatively small, there were not significant changes in temperature even from large pressure excursion. The largest temperature difference observed during this study was 0.2 °C.

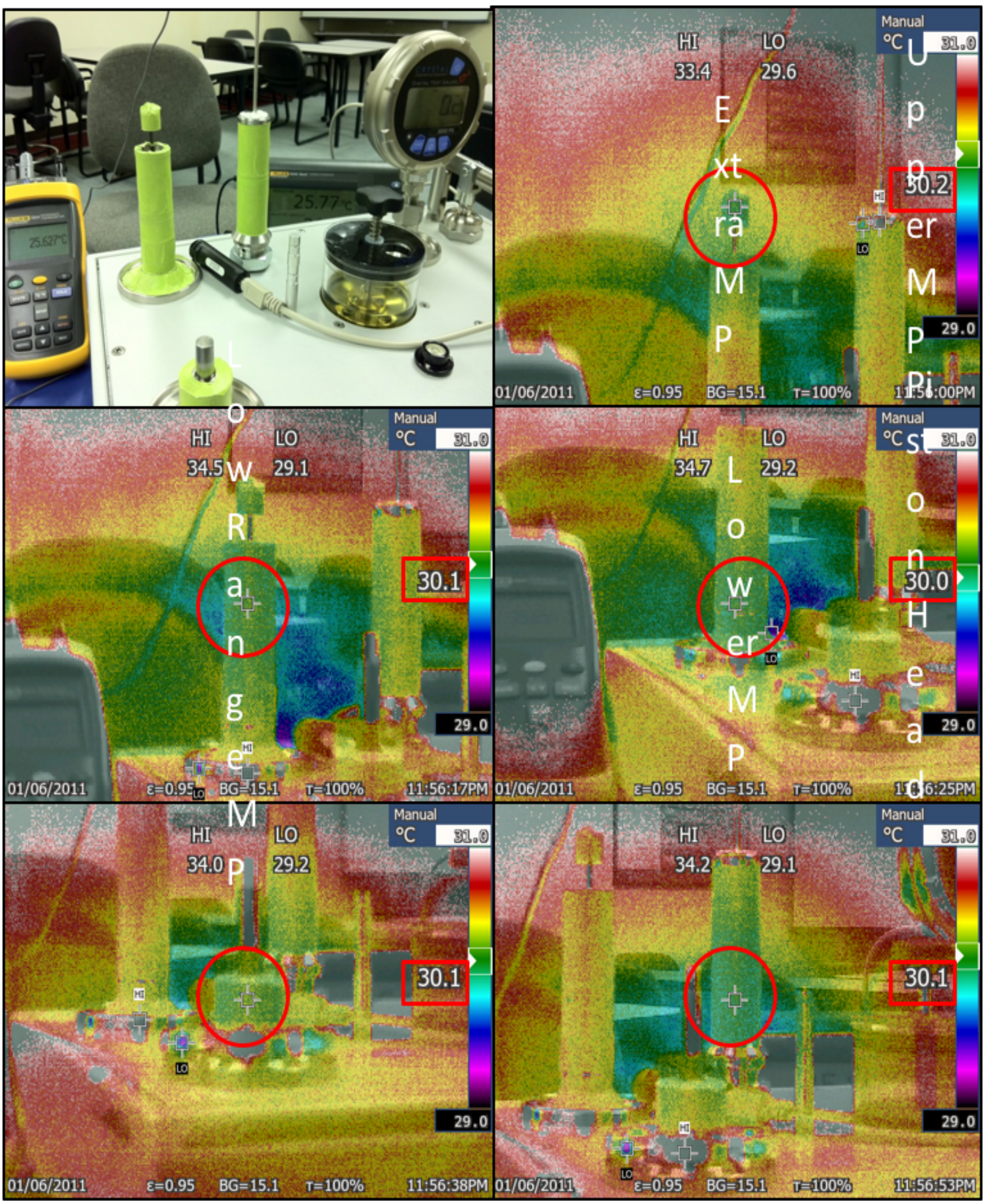
In conclusion, the uncertainty due to the assumption that the piston-cylinder temperature is equal to the ambient temperature is estimated

Figure A2. Chart of the difference in ambient and mounting post temperature in an uncontrolled environment.



to be ±1 ˚C (1.8 ˚F). In section 5.4 the uncertainty of the ambient thermometer is assumed to be ±1 ˚C (1.8 ˚F). Though the contributing factors are not correlated, a conservative estimate for uncertainty in piston-cylinder temperature is used of ±2 ˚C (3.6 ˚F) at k=2 as long as the fluctuations in ambient temperature are not greater than ±1 ˚C (1.8 ˚F) with average variations no more than 1 ˚C (1.8 ˚F) per hour.

Figure A3 Thermal images of a pressurized DWT



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Printed in U.S.A. 9/2012 4273963A_EN