Low Pressure Measurements

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Abstract

Low pressure (.2 to 5 psig) is one of the most rapidly growing segments of the pressure measuring market. It is, unfortunately, very difficult to make accurate calibrations of high accuracy gauge pressure instruments in this range. This paper discusses some problems and solutions found in making these types of calibrations. Techniques and types of necessary equipment for performing proper calibrations are discussed. The improved methods and the benefits in reduced uncertainty and time required for calibration are also discussed.

Beginnings

The conception of this paper lay in a customer's problem with the calibration of three 10 inch of water instruments. When compared against their pressure standards, the instruments were very non linear at the lower end of their range. The calibrations were checked using a variety of techniques and similar results were consistently received . These instruments had appeared very linear against two piston gauge primary standards before being shipped.

The instruments were returned and their calibrations were checked again. Again, they appeared very linear against the piston gauge standards. The only conclusions that could be reached was that something was wrong with either the process used for calibration or the standards. The only certainty was that the cause of the problem had to be determined.

The Calibration Looks Like What?

All of the instruments which are manufactured by Mensor receive a final calibration against primary standards which are piston type deadweight testers. As a case study, the calibration of one of the instruments is presented. It is characteristic of all three which had calibration problems. The final calibration curve against the corporate primary standards when the instrument left the factory is shown in Figure 1.

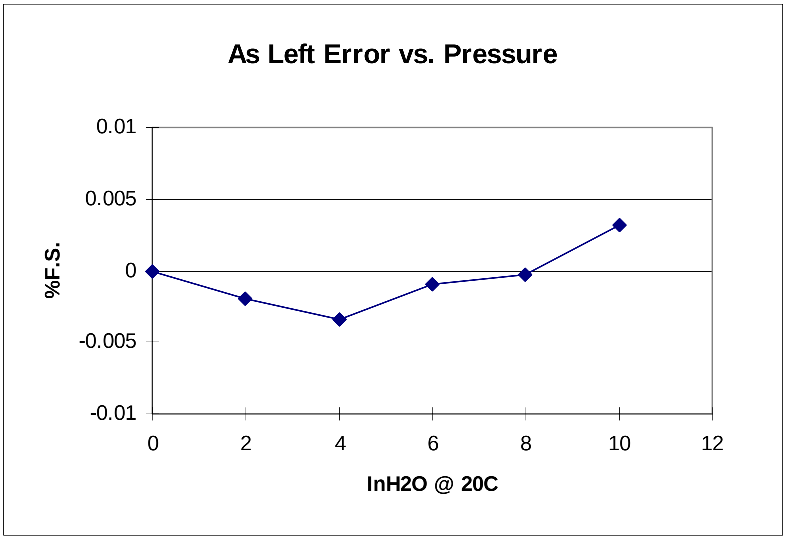

Figure 1. As Left 10 inH20 Calibration Curve

Now the results of the calibration performed against the customer's standards were very surprising. Mensor had historically had very good correlation between the calibrations of our instruments and this customer's standards so this discrepancy was troubling. Also, the calibration of all three instruments looked virtually identical. So, the repeatability of the calibrations was very good. Unfortunately the accuracy of them was very bad. After setting zero and span, the 10 inH20 sensors had a very peculiar shaped curve which is shown in Figure 2.

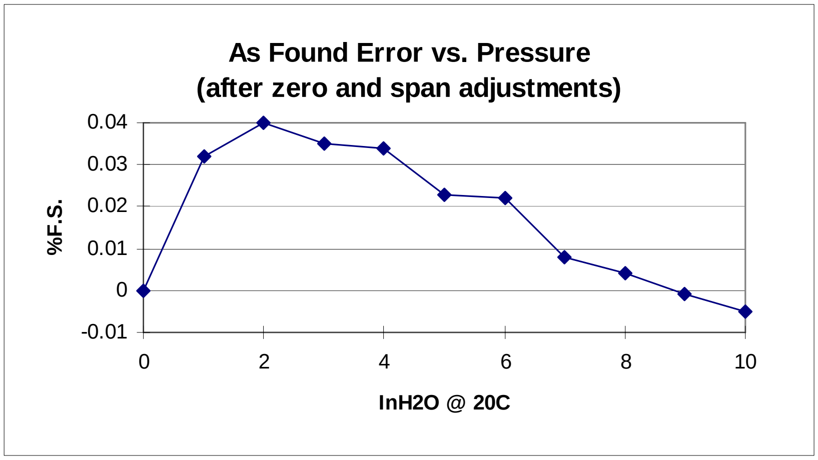

Figure 2. 10 inH20 Calibration Curve as Measured by Customer

If the calibration of the transducer was adjusted at the 20 and 100 percent points, the error curve would look like Figure 3.

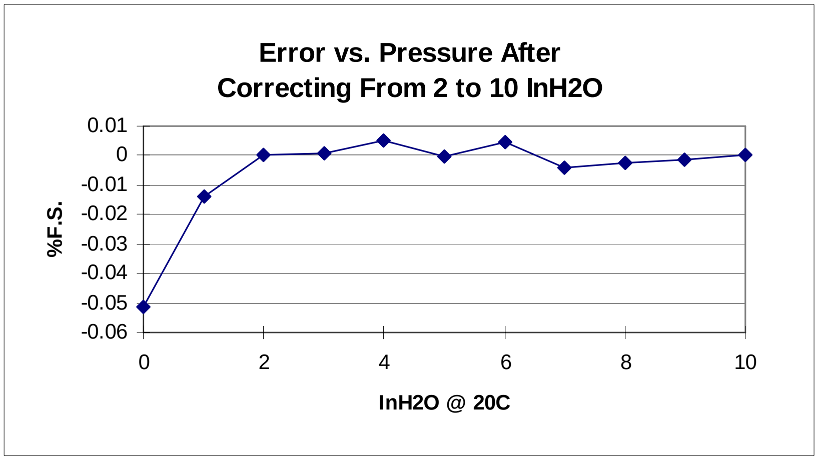

Figure 3. 10 inH20 Calibration Curve Without Zero Adjustment

The feature of this calibration curve which is interesting is that the correlation between Mensor's primary standards and the customer's was very good from 2 inH20 all the way to full scale, but got much worse at the low pressure end. To further investigate this phenomenon, some background is required on how the calibrations were originally performed.

Original Low Pressure Calibration Techniques

When differential or gauge instruments with less than 5 psi full scale were calibrated, a fixed reference pressure of approximately 1.2 psi was applied, and the pressure on the pressure port was varied from the pressure applied on the reference side to full scale. Figure 4 shows the test configuration.

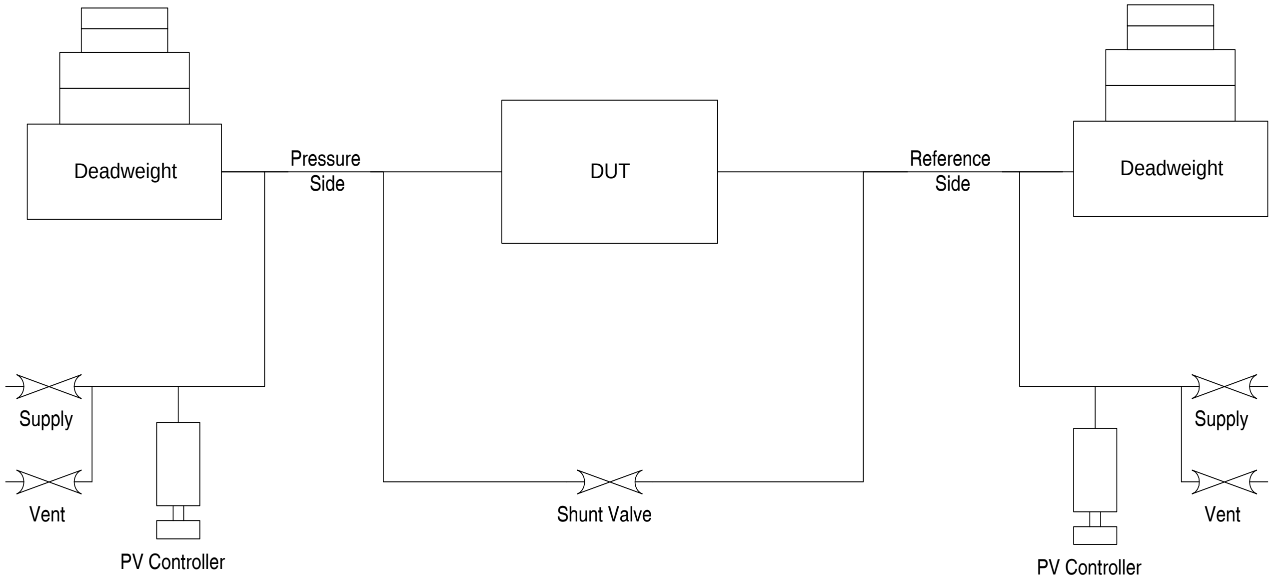

Figure 4. Sub-Tare calibration setup

The two deadweight testers were floated at the same pressure with the shunt valve open to achieve a zero nominal pressure. The DUT's zero was recorded, the valve was then shut and the rest of the pressures run.

This is actually a fairly common technique and has been documented for quite some time[1]. It is primarily used to get around problems associated with using deadweight piston gauges at the low end of their range. The primary ones of these are:

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[1] Gascoigne, J., *Precise pressure measurement in the range 0.1 - 500 torr*, Vacuum, Dec 17, 1970, pp 21-26

- The lowest pressure a vertical piston deadweight tester can generate is limited by the mass of the piston itself and its area.
- The pistons are difficult to keep spinning with no masses loaded on them.
- The accuracy and repeatability specifications of the pistons used in this test are degraded below 1 psi.
- At least 20% points need to be run on this type of DUT the lowest gauge pressure the primary standard deadweights could generate was .2 psi which wouldn’t allow calibration of an instrument with less than 1 psig full scale.

This technique has several drawbacks.

- It is expensive because two deadweight testers are required.
- It is technically difficult and time consuming to perform because two deadweight testers must be kept floating.
- The reference deadweight temperature must be checked and accounted for at each pressure point.
- It adds uncertainty to measurements because of the reference pressure effects of having pressure on both ports of a differential sensor.
- It adds uncertainty to the measurements because the accuracy specifications of deadweight testers are generally expressed as a percentage of reading. The pressure side deadweight tester is operating at a much higher pressure than the nominal differential pressure value being generated on the DUT.

For perspective, it should be mentioned that some newer technology pistons have the capability of generating much lower pressures. The pistons described in this paper have a nominal diameter of approximately 10.3 mm. Other pistons have diameters of 35 and even up to 50 mm. For a given piston mass, this will of course allow the piston gauge to generate much lower pressures. Also, pistons are being made out of less dense materials than tungsten carbide which has traditionally been used. This allows the pistons to have less tare mass which will again reduce the minimum pressure which can be generated.

Investigation of the Deadweight Pistons

The first path which was taken to resolve the problem was to reexamine the theories of how deadweights performed. Figure 5 shows the equation which is used to calculate pneumatic piston gauge pressures:

$$\text{Pressure} = \frac{\sum\left(M * \frac{gl}{gs} * \left(1 - \frac{\rho atm}{\rho mass}\right)\right)}{A * \left(1 + C_t * \left(T - T_{ref}\right)\right) * \left(1 + b_1 * P_{nom} + b_2 * P^2{}_{nom}\right)}$$

Where:	Pressure	Pressure generated by the deadweight
	M	Mass of individual weights
	gl	Local Gravity
	gs	Standard Gravity
	ρ_{atm}	Density of atmosphere surrounding masses
	ρ_{mass}	Density of masses
	A	Nominal area of piston at zero pressure and reference temperature
	Ct	Temperature coefficient of piston and cylinder assembly
	T	Actual temperature of piston
	T_{ref}	Reference temperature of piston
	b_1	First order compressibility coefficient of piston and cylinder
	P_{nom}	Nominal pressure being generated by piston
	b_2	Second order compressibility coefficient of piston and cylinder

Figure 5. Piston Gauge Formula

It is basically the equation reported by Heydemann and Welch[2]. The only difference is the b2 term which has been added by some deadweight piston gauge manufacturers[3] because of the non-linearity of the effective area of the piston over pressure.

Note that if the deadweight temperature and the atmospheric conditions are held constant, the pressure is linerally proportional to the mass, but not the area of the piston due to the first and second order compressibility factors. According to most deadweight manufacturers, and the theoretical analysis by Heydemann and Welch[2], these are negligible in the pressure range below 6 psig discussed in this paper. Theoretically then, the effective area of the piston should not change over pressure in this range.

Because of the fact that all three instruments had performed similarly, and the results of their calibrations were repeatable, it furthered the theory that there was something suspect with the effective area of the pressure side piston. The evidence of the poor calibration seemed to show that the piston on the pressure side of the DUT had a change in effective area with pressure. Subsequently the piston was sent off to have its area determined by a crossfloat procedure against a piston with an area known to 3 ppm. This was done using a completely different calibration chain than had been used on the piston before.

The piston was run from 1.2 to 25 psi three times. These runs were averaged. Figure 6 shows the results of this procedure.

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[2] Heydemann, P.L.M and Welch, B.E., Piston Gauges, Pure and Applied Chemistry, Reprinted from Experimental Thermodynamics, Volume II, Experimental Thermodynamics of Non-Reacting fluids, pp147-202

[3] Ruska Instrument Corp., Static Pressure Measurement Laboratory Manual, 1992, pp.

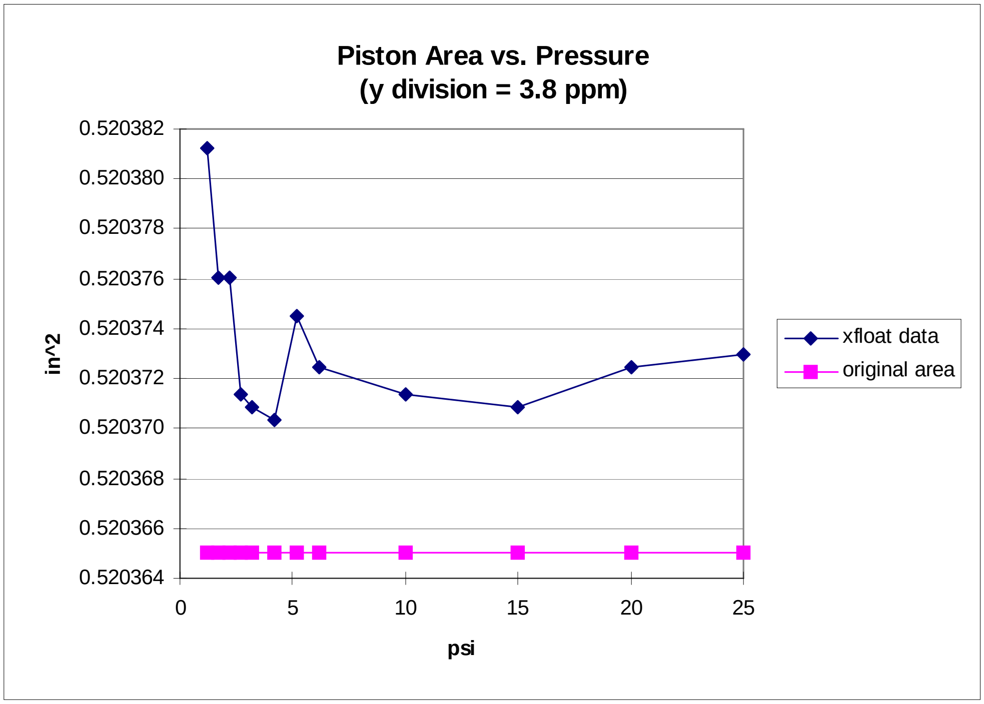

Figure 6. Cross Float Data for Pressure Side Piston

When this curve was first observed, it appeared that this was the source of the problem. The apparent increase in piston area at the bottom end of its range correlated to the direction of the low pressure linearity error of the DUTs in question. After calculating the magnitude of change (in a worst case from an effective area from .520381 to .520376), this would only amount to about a 0.003% error on a 10 InH2O instrument. Unfortunately, the errors of the DUT's were at least an order of magnitude worse. It should also be noted that the error in the area of the piston was well within its specified accuracy from its manufacturer.

Investigation of the Techniques

Since the errors in the DUT's could not be accounted for from the deviations of the piston area, the technique by which the low pressure calibrations was performed was reevaluated. The hardware being used was considered first, then the calibration techniques themselves were considered.

A calibration bench was designed and built which was physically symmetrical on both the pressure and reference sides. This was to prevent errors due to different time responses from the pressure and reference sides of the bench. All the compression fittings which were used previously were replaced with o-ring fittings to eliminate possibilities of leaks. Very small leaks can cause pressure gradients which are very small and might not be noticed at higher pressures but become very significant in the 10 InH2O pressure range. All the pressure and reference lines were insulated to prevent air currents from heating or cooling them and subsequently changing the pressures. Finally an extremely sensitive differential pressure cell was added to accurately determine the balance between the two deadweight testers at zero and to check the entire system for leaks. The new system is shown in Figure 7.

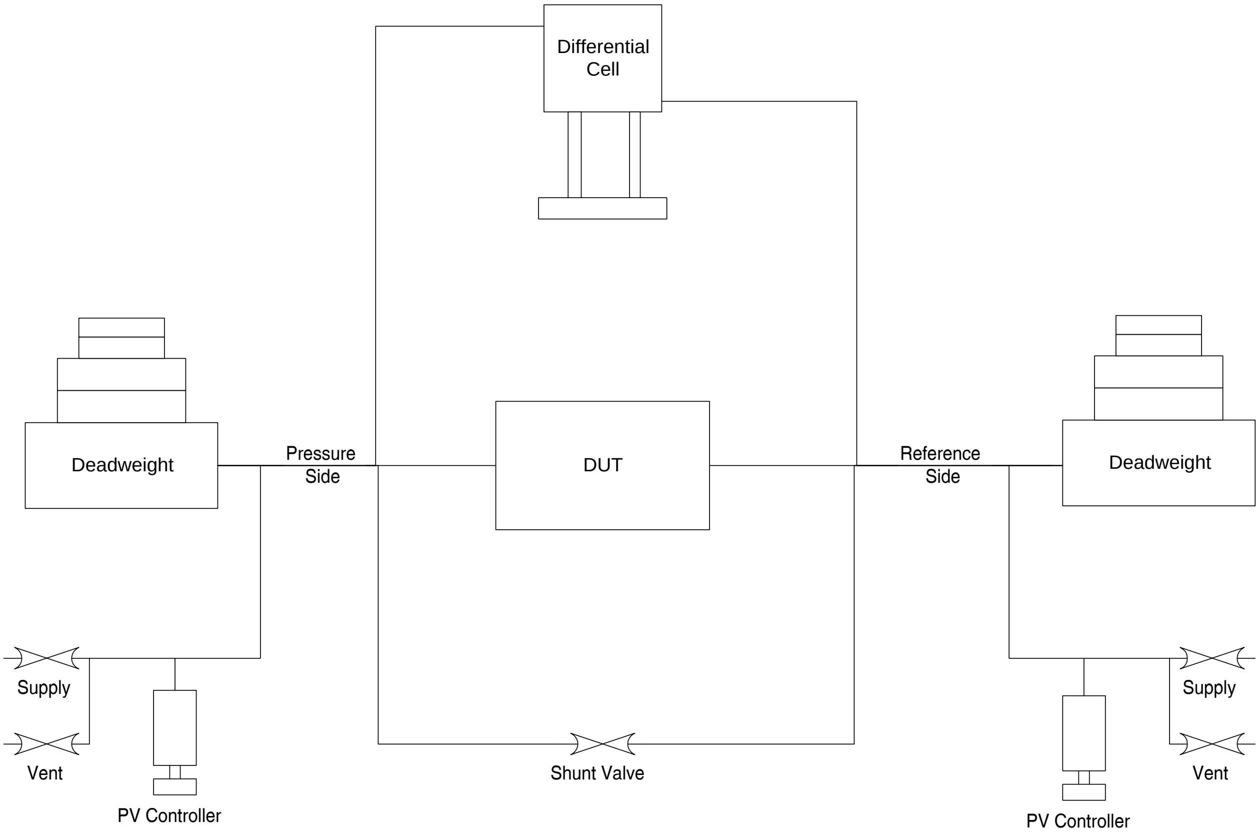

Figure 7. Low pressure Calibration Setup with DP Cell

The first major calibration technique flaw discovered was that the deadweight testers were generating pressures which were significantly off from each other when the zero reading was made on the DUT with the shunt valve open. The offset between the two deadweights at the tare pressure of 1.2 psi is well within their accuracy specs but becomes a very large factor when considered in the 10 InH2O pressure range. This would essentially cause the zero point to be non-linearly offset with respect to all the other calibration points because it was run with a different technique. This problem was resolved by leaving the shunt valve closed when both deadweight testers were floating and starting the calibration with the DUT adjusted to whatever the calculated differential pressure was between the two deadweights. The other alternative was adjusting the pressure of the reference side deadweight tester using small trim masses until the shunt valve could be opened or closed without either the DUT or the differential pressure cell showing any change in output. This process was much more time consuming than the first and it was determined to not cause any differences in calibration from the first technique.

The second major flaw discovered was that the compression fittings being used had a tendency to have minute leaks. The leaks were so small that the deadweight testers would float against them, but they were detectable with the differential pressure cell. When the shunt valve was closed, the indicator meter of the differential pressure cell would slowly swing one way or the other depending on which side had the leak. It should be noted that the leaks were not detectable with normal surfactant type leak detectors. These leaks were eliminated by using o-ring type fittings. The leaks would of course cause pressure gradients across the system since the pressure was not trapped in a static situation.

After these issues were resolved, the setup was tested at three different line pressures using the same piston deadweight testers to determine if the apparent low range non linearity was related to the pressure generated by the pressure side deadweight. Figure 8 shows the results of the three tests. From this graph, it is apparent that we were able to resolve the problem of the low pressure by improving the techniques used.

Another confirmation of this is the .14 psi line graphed on Figure 8. This was produced by running the same test with two floating-ball type deadweight testers at approximately 4 inH20 line pressure. This was performed to eliminate the possibility of systematic errors which we were not aware of in using the piston type deadweight testers.

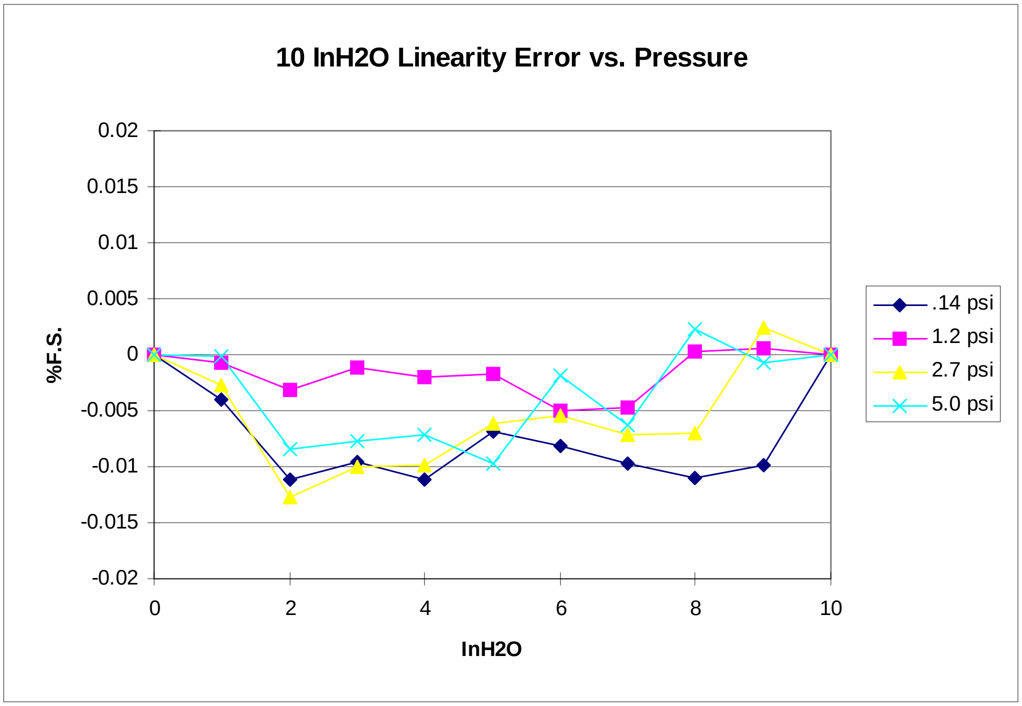

Figure 8. Linearity Errors of 10”H2O Gauge at Different Line Pressures

Uncertainty Analysis

Figure 9 shows the uncertainty analysis of pressure generated by the pressure side deadweight tester at 1.2 psi. The nominal pressure is calculated from the deadweight formula shown in Figure 5. The value column is for all the terms listed on the left. Each of these values which could change was varied by 1% and the new press column shows this effect on the nominal pressure. The sensitivity factor was then calculated as the change of the of the nominal pressure due to the 1% variation in the term in question. The stated uncertainty ppm column shows the uncertainty of each of the factors based upon manufacturers calibrations or some other calculations as in the case of the air density. Each of the stated uncertainties was then multiplied by the sensitivity factors to obtained corrected uncertainties. These were root sum squared together and the result multiplied by a coverage factor of 2 to achieve a greater than 95% confidence interval. This is the reported number at the bottom right.

Piston Gauge Uncertainty Analysis

Piston S/N: TL-135R
Mass Set S/N: 13788,13788-1
Cal Type: Gauge
nom press: 3.69334

Term	**Value**	**1.01*stand**	**new press**	**sensitivity factor**	**stated uncertainty ppm**	**Sensitivity corrected unc. ppm**
temp coef=	2.00E-05					
compr 1 =	0.00E+00					
compr2=	0.00E+00		3.73027			
gloc=	979.2463	989.038763	3.73027	1.0000000	5.11	5.11
gstand=	980.665					
p.area=	0.5203730	0.52557673	3.65677	0.9900990	11.43	11.32
density=	8.4					
ref.temp=	23					
dwt temp=	23	23.23	3.69332	0.0004600	10869.57	10.00
atm.press	14.5					
rh%	60					
amb. temp	20					
air density	**0.001188434**	0.00120032	3.69333	0.0001415	1602.26	0.23
Tare mass=	0.10409488	0.10513583	3.69533	0.0540761	10.00	0.54
r	1.300572	1.31357772	3.71829	0.6756327	10.00	6.76
h'	0.520302	0.52550502	3.70332	0.2702911	10.00	2.70
					rss:	17.53

	> 95% coverage	2
	Total Uncertainty:	**35.07**

Figure 9. Uncertainty Analysis of Piston Gauge at 1.2 psig

The uncertainties are calculated for the different line pressures at zero and span in the same fashion and listed in Figure 10. This also shows the effect of the uncertainty error of only the pressure side deadweight tester on the 10 InH2O gauge.

Line Pressure	10” Zero Point Uncertainty	10” Span Point Uncertainty	%FS error of 10 inH20	
			zero	span
1.2	35.07	35.80	0.012	0.015
2.7	36.99	36.25	0.028	0.031
5	34.07	33.47	0.047	0.050

Figure 10. Uncertainty Effects of Varying Line Pressures on a 10 InH2O gauge

The problem with this data is that while it may represent the uncertainty of one side of the differential test, it does not reflect the uncertainty of the test as a whole. Take the case, for example, at the zero point at line pressure. While the uncertainty of the line pressure may be large, the uncertainty of the zero point can be made very small if trim masses are used so that whether the shunt valve is opened or closed, the DUT reads zero.

Figure 11 presents a more thorough uncertainty analysis of the test at the span point of the 10 InH2O DUT. Because the DUT is zeroed at the tare pressure some of the uncertainties are reduced. One case is that the uncertainty of the masses needs only to be calculated on the additional masses required to produce the full scale value of the DUT. This analysis also eliminates the duplication of terms which affect both deadweight testers such as gravity which should only be considered once. A large factor which must be added to this analysis is the uncertainty associated with the repeatability of the deadweight testers. This value is based on the operating pressure of the deadweight which is many times larger than the range of the DUT.

Differential Uncertainty Analysis

Piston S/N: TL-135R, TL-1333
Mass Set S/N: 13788,13788-1,35697 **Cal Type: Gauge**

nom press: 0.36209

Term	**Value**	**1.01*stand**	**new press**	**sensitivity factor**	**stated uncertainty ppm**	**Sensitivity corrected unc. ppm**
plus temp coef=	2.00E-05					
plus compr 1 =	0.00E+00					
plus compr2=	0.00E+00					
plus p.area=	0.520373	0.5255767	0.35851	0.9900990	11.43	11.32
plus density=	8.4					
plus dwt temp=	23	23.23	0.36209	0.0004600	10869.57	10.00
minus temp coef=	1.50E-05					
minus compr 1 =	0.00E+00					
minus compr2=	0.00E+00					
minus p.area=	0.520372	0.5255757	0.35851	0.9900990	11.02	10.91
minus density=	8.4					
minus dwt temp=	23	23.23	0.36209	0.0004600	10869.57	10.00
gloc=	979.2463	989.03876	0.36571	1.0000000	5.11	5.11
gstand=	980.665					
ref.temp=	23					
atm.press	14.5					
rh%	60					
amb. temp	20					
air density	**0.001188**	0.0012003	0.36209	0.0001415	1602.26	0.23
mass j	0.130076	0.1313768	0.36459	0.6892422	16.95	11.69
mass k	0.052031	0.0525513	0.36309	0.2757001	42.39	11.69
3 grams	0.00662	0.0066824	0.36222	0.0350577	333.33	11.69

	ppm error	tare pressure	working pressure	
Tare Pres. Stab.=	3	1.2	0.36209	19.88

rss of type B's:	35.75
> 95% coverage	2
Total Uncertainty:	**71.51**

Figure 11. Uncertainty Analysis of Two Piston DWT's on a 10 InH2O DUT at 1.2 psi

One final point in observing this analysis is that it is reasonably close to doubling the uncertainty of the pressure side piston analysis shown in Figure 9. This would however not be the case if the analysis were made at 10% or 20% of the range of the DUT. The total uncertainty would increase many times because of the sensitivities of the final pressure to the masses and the tare pressure stability.

Conclusions

1. Use extreme care in determining if the calibration system has any leaks. They could be extremely small and still cause significant pressure gradients for low pressure calibrations.

2. Make sure to collect all data points using the exact same setup for each point - especially zero.

3. Use the lowest reference pressure practical to eliminate reference pressure effects on the DUT.

4. The total uncertainty of the test should be carefully calculated at each point because it can be much greater than just the accuracy of the pressure side pressure standard - especially at the lower pressures.

5. Select standards which are not only accurate but also very stable.