A Method for Verifying Traceability in Effective Area for High Pressure Oil Piston-Cylinders

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Abstract

Fluke Calibration has defined traceability in effective area of a piston-cylinder through the Piston Cylinder Pressure Calibration Chain since 1983 [1]. The calibration chain effective area traceability is primarily based on dimensional measurements for a low pressure piston-cylinder with a diameter of 50 mm, and an integration method to calculate the effective area based on the dimensions of the piston and the cylinder [2, 3]. The effective area for smaller piston-cylinders that constitute the calibration chain and define pressure traceability to 500 MPa (72500 psi) are determined through crossfloat intercomparisons called Base Ratio crossfloats [1, 4]. This method used to define traceability for higher pressures is dependent upon the elastic deformation coefficient, i.e. the change in effective area as pressure increases, and requires some extrapolation of the change in effective area. Because of this, each time the calibration chain is re-established there is some method of measurement assurance at higher pressure that is performed. In 2001 and 2004 the measurement assurance was achieved by comparing calibration chain piston-cylinders to a piston-cylinder that had been determined by LNE (France) in the late 1990s up to 200 MPa (30,000 psi). In addition to this in 2004 a second comparison was performed with NIST (USA) also to 200 MPa.

The Fluke Calibration Piston Cylinder Pressure Calibration Chain was re-established in 2010. In lieu of sending another piston-cylinder to an NMI pressure laboratory to verify the calibration chain an alternative method was established and completed based on a method described by Dadson, Lewis and Peggs of NPL (UK) [7]. This paper discusses this method and provides the results and an uncertainty budget.

Learning Objectives

Readers and attendees will learn about how pressure traceability is achieved at the highest level over a very wide range. In addition to this they should learn how Poiseuille's Law applies to high pressure oil piston-cylinders.

1. **Introduction**

There is no question that it is challenging to maintain traceability of all measurands at the highest level. Fluid pressure, a derived unit, is no less difficult. Traceability at higher pressures continues to be a challenge for national metrology institutes. A good indication of this is that the methods used to reach traceability tend to vary between the most prominent national metrology institutes. This is also represented in their uncertainties. Querying some major national metrology institute's CMC uncertainties show more consistent uncertainties at low pressures, but at higher pressures, for instance at 200 MPa (30,000 psi), the relative uncertainties can vary from ±0.003% to ±0.02%. This is most likely due to the fact that the traceability is maintained through piston gauges and higher pressure becomes dependent upon the knowledge of the physical properties of the components of the piston gauge, primarily the change of the piston-cylinder's effective area as pressure gets higher.

The Piston-Cylinder Pressure Calibration Chain (CalChain) is Fluke Calibration's (Phoenix) accredited reference for the effective area of piston-cylinders. The uncertainties maintained in effective area determination by the CalChain are very low. In comparison to the uncertainty range stated in the previous paragraph, Fluke Calibration is accredited to ±0.0028% relative pressure uncertainty at k=2 at 200 MPa. The CalChain has been described in two NCSLI papers, one in 1989 [1] and also in 2002 [2]. The CalChain was re-characterized in 2010 and Figure 1 shows its configuration.

To summarize without getting into the excessive detail from previous papers, referencing Figure 1, the calibration chain provides traceability in effective area from approximately 5 kPa (0.725 psi) to 500 MPa (72,500 psi). This is accomplished by an extensive amount of crossfloat comparisons called the Base Ratio crossfloat. Each line in Figure 1 is at least two of these crossfloats to develop a ratio between the respective piston-cylinder effective areas. Traceability begins at low pressure with the 50 mm diameter piston-cylinders serial numbers 1161 and 407 and is transferred through these comparisons by a method described in the original CalChain paper [1]. There is a transition between gas and oil operated piston-cylinders at the 0.1 to 10 MPa level. These are piston-cylinders that can be used both in gas and oil and are not mentioned in the previous papers [1, 2]. For each step that takes the traceability to a higher pressure, i.e. transferring effective area from one range to the next, there is extrapolation. This extrapolation comes from the elastic pressure deformation coefficient of the piston-cylinders. This coefficient can be either theoretical or measured.

The uncertainty of the theoretical pressure coefficient is dependent on the design of how a piston-cylinder mounted, the uncertainty of the values used for elastic properties, and the method that is used to calculate the theoretical value [5]. For the CalChain theoretical pressure coefficients are used up to the 100 MPa level. The CalChain then uses measured pressure coefficients for the 200 and 500 MPa levels using the lower range piston-cylinders and SN 27D (described later) as the reference for the pressure coefficients.

The uncertainty of the theoretical pressure coefficient is considered to be ±10%. However because of the structure of the CalChain, errors in the pressure coefficients would show up in what are called loop errors. Loop errors are deviations when calculating the same ratio between two effective areas but through different paths [1, 2]. But because the 200 MPa level piston-cylinders are measured from the 100 MPa level theoretical pressure coefficients and SN 27D, and the fact that there is some slight possibility that the method for calculating the theoretical pressure coefficients could have a global systematic bias, it is always deemed necessary to validate the CalChain at a significantly high pressure. Traditionally this has been performed at the 200 MPa level.

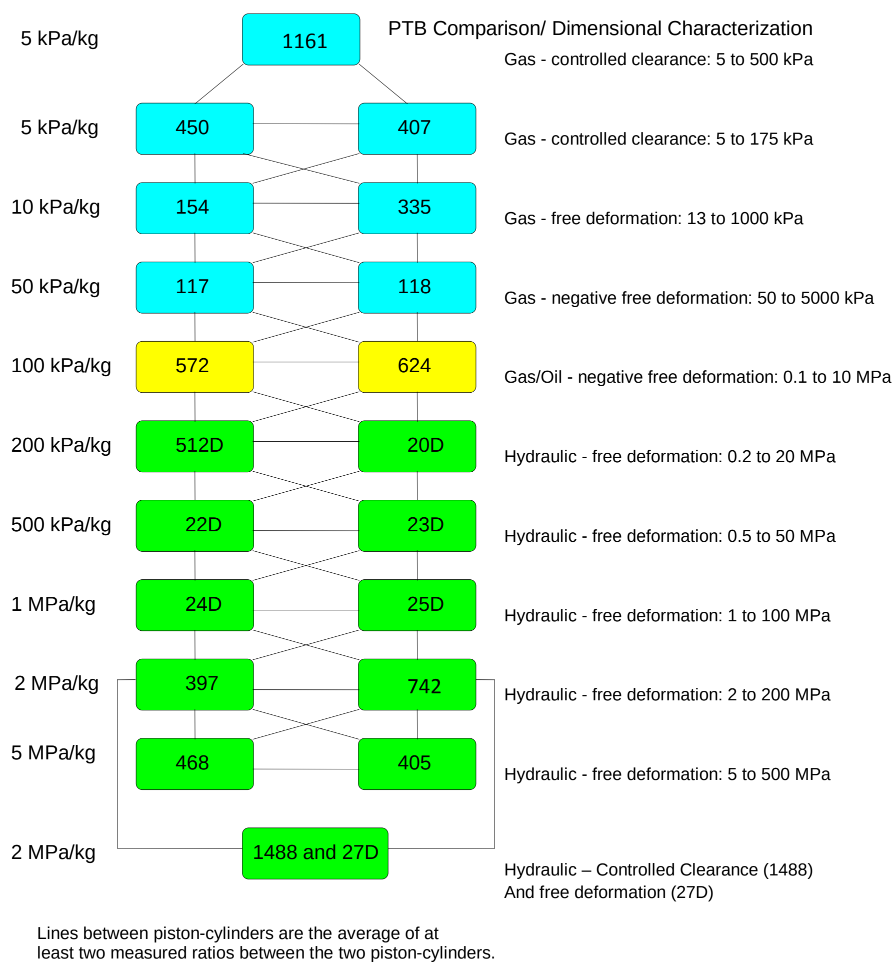

Figure 1. Configuration of the Piston-Cylinder Pressure Calibration Chain

2. Methods of Validation

For the 2010 CalChain there were three methods of validation. One was a comparison up to 280 MPa with the Fluke Calibration Houston facility (Ruska) [6]. This was performed in January 2011 in Phoenix and showed that agreement was within the accredited pressure uncertainties, of which are primarily supported by the CalChain. The results are shown in Figure 2.

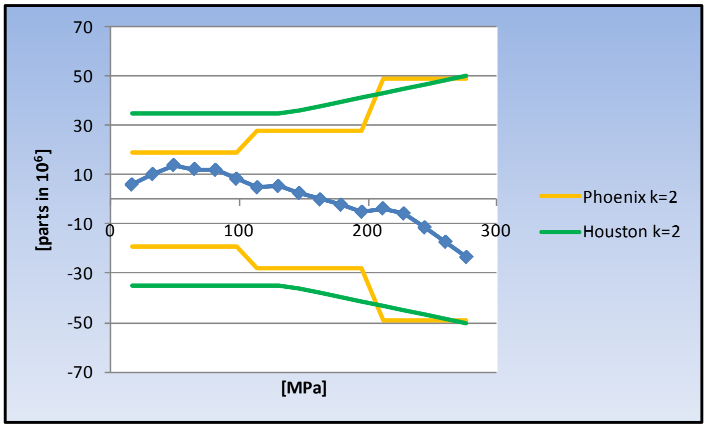

Figure 2. Agreement in pressure between Houston and Phoenix January 2011 - 16 to 280 MPa.

The second method was by comparison to 2 MPa/kg (2 to 200 MPa range, 300 to 30,000 psi) piston-cylinder serial number 27D (formerly SN 26). This piston-cylinder was originally calibrated by NIST (USA) in 1993, recalibrated in 1998 by LNE (France), and then re-determined by NIST in 2004. 27D effective area was determined again in 2010 using the new CalChain. Figure 3 shows the agreement of the results of the three NMI determinations with the average of the three determinations and how the determination performed in 2010 by the CalChain compares to them.

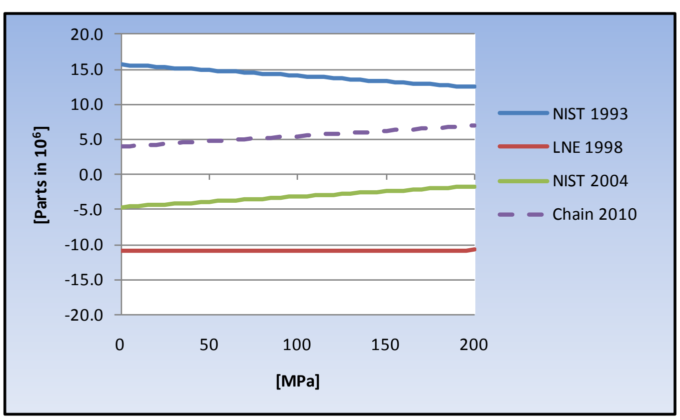

Figure 3. Comparison of effective area of SN27D measured by NIST, LNE and 2010 CalChain.

The accredited relative uncertainty from 2 to 200 MPa in effective area of a 2.5 mm (2 MPa/kg) piston-cylinder is ±0.002%. This results in an accredited relative pressure uncertainty in the same range of ±0.0028%. Both of the first two methods indicate that the CalChain is operating within stated uncertainties. However, as good as they were, it was noted that these verifications were dependent upon traceability that is at least 7 years old. Though the tungsten carbide piston-cylinders have excellent stability, as shown in Figure 3, it was decided to pursue newer traceability.

The first consideration was to send out 27D to be re-calibrated by an NMI. Unfortunately after reviewing the options available, it seemed that either the uncertainties were not that supportive or the costs were prohibitive. A new method was then considered that was performed in 2004 with some success but never published. The method is simple in theory and described in Dadson, Lewis and Peggs, The Pressure Balance, Theory and Practice and is called the single piston method [7].

3. Single Piston Method Validation

What is important to understand about the use of this method as it is described in this paper is that it is not intended to be used to calibrate a piston-cylinder over its pressure range. It is only intended to validate the results of the CalChain. The test plan includes the use of PG7307 controlled clearance, 2.5 mm (2 MPa/kg), SN 1488, and was as follows.

- Determine the effective area of SN 1488 with zero controlled clearance jacket pressure using both CalChain 2.5 mm piston-cylinders up to 200 MPa using the Base Ratio crossfloat method. The result of this is an effective area at 20˚C and zero pressure as determined by the CalChain.

- Dimensionally characterize SN 1488 2.5 mm piston at NIST.

- Perform drop rate tests to determine the average gaps at various pressures and various controlled clearance jacket pressures (CCP) and plot those gaps with respect to pressure to obtain an average gap at zero pressure.

- Using the zero pressure gap and dimensioned piston, calculate the effective area at zero pressure and 20˚C and compare to what was determined from the crossfloats.

3.1 Effective Area Determination through Crossfloat

Table 1 gives the results of the crossfloats performed on 1488. Given are the average ratio for each pressure and each CalChain reference, the calculated effective area at zero pressure and

20˚C, two standard deviations of the average effective area, and the elastic deformation coefficient determined by the crossfloats at zero controlled clearance pressure. The average $Ae_{(20,0)}$ is what is compared to that determined using the single piston method.

Table 1. Results of Base Ratio crossfloats of SN 1488 at 0 controlled clearance pressure

Pressure	Ratio from 742 at 0 MPa and 20˚C	Calculated $Ae_{(20,0)}$	Ratio from 397 at 0 MPa and 20˚C	Calculated $Ae_{(20,0)}$
[MPa]	[---]	[mm^2]	[---]	[mm^2]
40	0.9996962	4.9033917	0.9999149	4.9033921
80	0.9996991	4.9033772	0.9999150	4.9033920
120	0.9996994	4.9033759	0.9999143	4.9033950
160	0.9996986	4.9033797	0.9999113	4.9034097
200	0.9997013	4.9033667	0.9999119	4.9034069

Average $Ae_{(20,0)}$	4.9033887	mm^2
2 standard deviations of all $Ae_{(20,0)}$	5.6	Parts in 10^6
Elastic Deformation	7.75×10^{-7}	MPa^{-1}
Uncertainty (k=2)	20	Parts in 10^6

3.2 Effective Area Determination through Single Piston Method

In December 2010 NIST dimensioned two 2.5 mm pistons using the lowest uncertainty commercially available. One was SN 1488 and another was a slightly smaller piston to be used in a different study. The dimensions were diameters on Z axis corresponding to the engagement region of the piston performed at orthogonal planes.

Figure 4. SN 1488 piston showing engagement region.

Figure 4 shows the engagement region of the piston. The measurements were taken +1.5 to -1.5 mm of the centered engagement region to allow for the movement of the piston when performing the drop rate tests. The uncertainty of the diameters was ±0.043 µm, at k=2. Table 2 gives the results of the determination, including each diameter and the average of each diameter Z axis level.

Table 2. Results of 1488 2.5 mm piston from NIST

Z Position [mm]	0 deg [mm]	90 deg [mm]	Average [mm]
16.5	2.498181	2.498176	2.498179
13.5	2.498211	2.498203	2.498207
10.5	2.498183	2.498188	2.498186
7.5	2.498099	2.498126	2.498113
4.5	2.498146	2.498151	2.498149
1.5	2.498154	2.498169	2.498162
-1.5	2.498158	2.498193	2.498176
-4.5	2.498164	2.498179	2.498172
-7.5	2.498098	2.498114	2.498106
-10.5	2.497951	2.497988	2.497970
-13.5	2.497898	2.497903	2.497901
-16.5	2.497723	2.497763	2.497743

The average of the total diameter was calculated from all diameters to account for the fact it would be combined with average gap at zero pressure and 20°C. The average value for the piston diameter was then 2.498088 mm.

3.3 Gap Determination

One of the reasons that this method was chosen was due to the fact that the average gap could be determined with a very low uncertainty. Equation 1, derived from Poiseuille's equation for viscosity [7], shows the equation for determining the gap for an incompressible fluid.

$$h = \left(\frac{\eta 6 L R V_{fl}}{P_{gauge}} \right)^{1/3} \qquad (1)$$

Where:

Variable	Description	Unit
h	Average gap in the engagement length of the piston-cylinder	m
L	Length of the gap	m
R	Radius of the piston	m
V_{fl}	Volume flow determined from the drop rate	m^3/s
P_{gauge}	Gauge pressure at the determination	Pa
η	Dynamic viscosity of the fluid used in the drop rate tests	Pa•s

Considering that the effective area is approximate 4.9 mm^2, a 0.02 µm gap uncertainty represents 16 parts in 10^6 in effective area. The typical gap of this type of piston-cylinder is approximately 0.5 µm. This means that the gap determination only needs to be within 4%. Considering that all the variables in the equation have a sensitivity of approximately 0.33, and that there is a known characterization of viscosity over the temperature and pressure range the testing was performed with an uncertainty less than 3%, it seemed this uncertainty could be achieved.

The drop rates were performed at three different controlled clearance pressures; 0, 25 and 50% of the measured pressure, and at various pressures from 12 to 200 MPa for the 0% CCP, and 40 to 200 for the 25 and 50% CCP. The non-contact inductive electronic piston position indicator that is integrated in the design of the PG7307 was used to measure the drop rate. This was a stroke of luck because the drop rates were originally going to be taken by a mechanical drop indicator. But the contact of the drop indicator on the top of the piston produced just enough friction to significantly reduce the amount of free spin time. In addition to this, if the drop rate was low, the drop indicator was sticking and not repeatable. A test was then performed to compare the non-contact inductive drop indicator in the base compared to the drop indicator at one of the faster drop rates. This showed that the piston position indicator in the base was linear and stable enough to measure the drop rates. This was well within the expectations of the indicator. Otherwise another non-contact method would have been necessary, such as a laser interferometer. The drop rates were strategically run from +1.5 mm to -1.5 mm. This was to match the dimensional measurements taken on the piston. For each CCP and pressure there were at least three drop rates performed. Piston position and mounting post temperature were read by interfacing software to automate the tests. There ended up being 64 tests that were performed in late 2010 and early 2011.

What was very crucial to the success of the repeatability and uncertainty of the volume flow measurements was the piston position uncertainty and the uncertainty of the compensation of the volume flow with changes in temperature. The first assumption of the volume flow was fairly accurate. Only the uncertainty of the piston position sensor in the region tested and the uncertainty of the area, which is very well known, are considered. The fluid used was Monoplex DOS (Di-2-Ethylhexyl Sebacate). If the temperature changed during the test the volume flow calculations would be severely affected by the thermal expansion of the Sebacate. To minimize this effect the isolation valve was placed directly outside the PG7307 base. This minimized the volume that could change from temperature and helped to insulate the affected volume from the outside lab temperature. The predicted volume was approximately 5 cc. Also to predict the changes in volume throughout the test the mounting post temperature was read automatically the same time the piston position was read. During the drop rate tests if the measured pressure was changed, at least 60 minutes of stability time was observed to allow for the fluid to equalize with the temperature of the mounting post. In no test did the temperature change more than 0.03 °C. The volume change during the test was compensated by any slight changes in temperature due to the thermal expansion of the fluid. The average temperature during the test was used for viscosity calculations. Rotation times were kept between 10 and 30 RPM to minimize any heating effects caused by rotation and to ensure the piston was centered inside the cylinder.

What was also beneficial to this method was the knowledge of viscosity. Dadson [7] suggests a two piston method when the viscosity is not well known, but this would have been an excessive amount of work and analysis. A characterization of DOS was performed in the early ‘90s, over the temperature and pressure range needed for the drop rate tests, with an uncertainty of ±3% [8].

Table 3 gives the results of the gap determinations for each controlled clearance pressure and measured pressure. Included on the last row is the intercept linear regression to determine the gap at zero pressure.

Table 3. Gap determinations for piston-cylinder SN 1488.

Pressure	0% CCP	25% CCP	50% CCP
[MPa]	[um]	[um]	[um]
200	0.9482	0.6932	0.4756
160	0.8840	0.6681	0.4830
120	0.8126	0.6386	0.4994
80	0.7253	0.6221	0.5157
40	0.6240	0.5800	0.5321
12	0.5657	----------	----------
0	**0.5488**	**0.5587**	**0.5449**

It should be noted that the gap determinations do not have to be corrected for thermal expansion of the piston-cylinder because the piston and cylinder are made of the same material and expand the same amount. Figure 5 shows what is presented in Table 3 graphically.

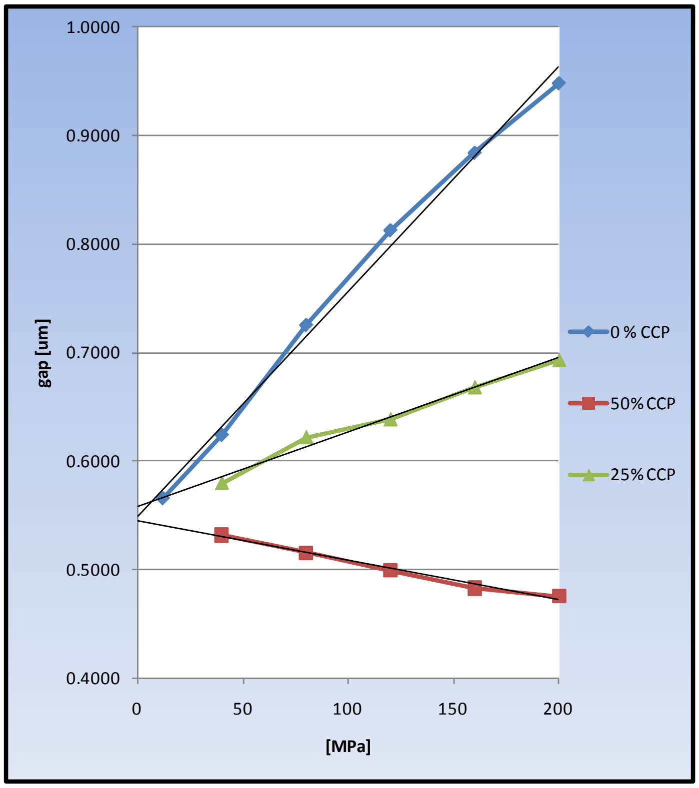

Figure 5. Plots of gaps at the three CCPs

3.4 Results

Though there was some variance, the intercepts for the three plots were within standard error of the fit at 95% for the regressions. Using the average piston radius and the average of the gaps at zero pressure, the result effective area at 20˚C and zero pressure is 4.9033956 mm^2. This is 1.4 parts in 10^6 (0.00014%) different from what was determined through the crossfloats and is obviously well with the ±0.002% relative uncertainty in effective area at k=2.

3.5 Uncertainty

In this case the result was much better than the uncertainty. Table 4 provides the uncertainty budget of the effective area determined by the single piston method. This section does not provide the details of the uncertainty analysis, but it is easy to identify the largest contributor. Approximately 90% of the uncertainty was contributed by the uncertainty of the diameter of the piston as measured by NIST which was ±43 um. As noted previously, relatively large uncertainties in volume flow and dynamic viscosity had little effect on the final uncertainty.

Table 4. Uncertainty budget of the effective area at zero pressure for the single piston method.

	k=1	Sensitivity	Unc (h) k=1
	[% relative]	[% of 0.550 µm]	[µm]
V_{fl}	0.234%	0.33	0.00043
R	0.034%	0.33	0.00006
L	0.050%	0.33	0.00009
P_{gauge}	0.250%	0.33	0.00046
η	3.000%	0.33	0.00549
h		Combined	0.0055
	k=1	Sensitivity	U radius k=1
	[µm]	[µm/µm]	[µm]
Piston Diameter	0.0215	0.5	0.0108
h (from above)	0.0055	0.5	0.0028
h std error of fit	0.0076	0.5	0.0038
		Combined	0.0117
		Expanded (k=2)	0.0235
		Radius	0.0019%
		effective area	0.0038%

The final expanded uncertainty in radius, in µm, is also given as a relative value for radius and effective area and is ±0.0019% and 0.0038% respectively. Though the effective area uncertainty is higher than that from the CalChain, it is close to what would have been received if sent to an NMI, and is significantly less expensive. And though this is evaluated as k=2 it is considered to have a high degrees of freedom due to the fact that the main contributors were from NIST dimensional measurements, the volume flow, and viscosity, where the reported uncertainty was 3% at k=1 [8].

If the uncertainty in piston diameter were on the order of ±20 um, then the final uncertainty in radius would have been ±0.014 µm and the final uncertainty in effective area less than ±0.002%. There are NMI's that offer lower dimensional uncertainties for external diameters in this range, but the service provided NIST was far too attractive to look for an alternative.

4.0 Conclusion

The Fluke Calibration Piston-Cylinder Pressure Calibration Chain maintains uncertainty in effective area at a level that is comparable to the best NMI pressure groups. In order to validate the high pressure effective area determinations that are dependent upon the knowledge of elastic deformation it is advantageous to have more than one method for this validation. Considering all three methods are well within the stated uncertainties there is high confidence in the CalChain results.

The single piston method as it is described in this paper is not intended to be a full characterization through 200 MPa such as NIST's evaluation of the same size piston-cylinder performed 2003 through 2005 using the Heydemann and Welch method [9]. The method described in this paper was only to validate the CalChain by comparing calculated effective areas at zero pressure. Also, as good as the results were, there is more study to be done to ensure that the warnings of Olsen [9] and Dadson [7] are not significant. These are that the deviations in concentricity of the piston inside the cylinder are not producing an excessively large calculated gap from excessive flow, and that the deviations in geometry for the piston and the cylinder ('u' and 'U' in Dadson) do not excessively affect the pressure distribution in the gap. Because of some taper in the piston, the latter affect was experienced if the drop rate tests were not performed in the same range that the piston dimensional measurements were used. It is interesting to note that both times this study was performed, the results of zero pressure gap using different jacket pressures produced results that agreed with the different CCPs. Since the distributions of pressure must be significantly different at the different CCPs, yet still produce the same result within the uncertainty of the gap calculation, this suggests these affects are minimal.

The next step is to perform a study such as the Heydemann and Welch model or FEM. This is attractive since many of the measurements have already been taken. This would produce a reference instead of a validation tool. Also with the benefit of having the second smaller piston measured, the similarity method can be used in a separate study.

5.0 Acknowledgements

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6.0 References

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