

# THE STATE OF PRESSURE UNCERTAINTY

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Abstract - Recent NIST calibrations of Ruska Calibration Laboratory primary standard deadweight gauges resulted in reduced uncertainty estimates for the assigned effective areas. The new area coefficients and uncertainty estimates have been transferred through the chain of Ruska transfer standards to the commercial instruments we supply and maintain for industry. Detailed uncertainty analyses document the transfer of the new uncertainty estimates through the calibration chain and demonstrate how these improvements can be realized at all levels of pressure measurement.

## Background

Through the 1960's, 70's and 80's the classic uncertainty estimate for laboratory-level deadweight gauge pressure measurements was typically between 0.01% and 0.015%—in the latter years, an arguably conservative value. Over the last decade, the uncertainty for such pressure measurements has become significantly lower.

Several factors contributed to these reductions in the early and mid-90's, particularly for the lower pressure gas deadweight gauges. Documented evidence of performance and extremely long term stability led to better performance ratings; improved capabilities at the national standards level led to lower uncertainties at the top level; more refined and more universal methods for combining uncertainty components made the uncertainty estimates more consistent and reliable.

Now, with even more complete historical records of performance and stability, ongoing reductions at the national standards level, and further refinements to the detail of the uncertainty analysis, the new uncertainty estimates for the low pressure gas deadweight gauges have crossed a threshold—a factor of ten lower than just 10 years ago.

## Revised Uncertainty Expression

This paper discusses the key influences in the new analyses of the low pressure gas deadweight gauges—improvements at the fundamental level at NIST, refined uncertainty analysis techniques, and supplemental historical records—to demonstrate the level of attention the field of pressure measurement has attained in recent years. The largest of these recent improvements is the direct result of advancements at NIST. Other significant improvements were recognized by refining the detail in the formal uncertainty analysis. In particular, a more detailed analysis of the composite mass load uncertainties, and a more thorough assessment of historical records of performance and long-term stability.

## Fundamental Changes at NIST

The previous path of traceability for the Ruska low-pressure gas deadweight gauges lead to a fundamental standard at NIST, the gas thermometer manometer (GTM). This manometer was used to characterize the effective area of a conventional gas lubricated piston/cylinder assembly in the absolute mode. The uncertainty in the assigned effective area was just two parts per million (ppm) at the 95% level of confidence. At that time, there was significant concern of a potential mode dependant effect on area, but the GTM was not configured for gauge mode operation and no characterization of the mode effect could be performed. Since a large percentage of deadweight gauge pressure calibrations are performed in the gauge mode, the uncertainty in the effective area determined via the GTM path was increased by 10 ppm to account for the potential mode effect.

As shown in Figure 1, the new path of traceability for Ruska low-pressure gas deadweight gauges leads to a different fundamental standard at NIST, an ultrasonic interferometer manometer (UIM). Since the UIM operates in both gauge and absolute modes, the effective area of the top level Ruska transfer standard, piston PC-14, was characterized in both modes. Although the uncertainty in the effective area determined using the UIM (5.7 ppm) is higher than the 2 ppm uncertainty achieved using the GTM, no additional uncertainty component is needed to account for mode effect. This results in nearly a 45% reduction from the uncertainty in the GTM path when adjusted for the potential mode effect.

## Uncertainty Analysis Template

Other key elements of the new uncertainty expression are in the detail of the analysis of certain component uncertainties, and in the refinement of the format and content of the template used to simplify and standardize the analysis process. Although all of the calibrations in this traceability path involve conventional deadweight gauges, and all the same influences affect each deadweight gauge, the impact that certain parameters have on the end product vary with the type of comparison. The uncertainty analysis template optimized for a deadweight gauge pressure calibration is generally inadequate for analysis of a crossfloat calibration.

Analysis of routine deadweight gauge pressure calibrations is rather straightforward—the key influences are well understood, and a sample uncertainty analysis has been available for some time in NCSL RISP-4, a guide for expressing deadweight pressure gauge measurement

uncertainties [1]. However, an example for estimating the uncertainty in effective area derived from the deadweight gauge crossfloat process is not yet included in this guide.

### Pressure Calibration Template

Uncertainty analyses performed at Ruska for low-pressure gas deadweight gauges are facilitated by using a computer spreadsheet template. The template is based on the example given in NCSL RISP-4 [1] with a few simple modifications. As shown in Table 1, the main changes include the addition of a few parameters and rearranging the parameters into influence categories—effective area, force and system-related factors. A column was also added to show the expanded uncertainty for each influence in parts per million of the end product, pressure. Other changes are primarily cosmetic.

### Crossfloat Calibration Template

Members of the NCSL RISP-4 development committee have been reviewing a sample crossfloat calibration uncertainty analysis, provided as an example by a NIST representative. The committee may decide to incorporate this example into a future release of the RISP-4 guide, perhaps with some modifications. Until such a reference becomes commonly available, we must make due with templates or formats that might vary more widely between organizations.

The crossfloat calibration uncertainty analyses performed at Ruska are based largely on the sample being reviewed by the RISP-4 committee. The key modifications or enhancements made to this format primarily affect the way that certain correlated influences impact the final effective area determination. Further consideration is given to those influences whose effect contributes primarily to the scatter in the effective area fit residuals [1, 2].

### Special Factors

#### Pressure Calibration System Mass Load Correlations

The mass calibration process results in an error in each mass determination that is a composite of the error in the standard and the variability in the calibration process. Of the numerous individual weights in a typical deadweight gauge weight set, some of the weights have the same approximate mass. As such, they are typically calibrated using the same standard mass. The error in the standard mass is passed on equally to each of the same-denomination weights, and the uncertainty in the reported mass value includes the uncertainty in the standard mass. The uncertainty in the standard mass becomes a correlated uncertainty for all of the same-denomination weights. Such correlated uncertainties cannot be combined in quadrature, as is the general condition for most other uncertainty components. An example for the treatment of such correlated uncertainties is given in the ISO Guide to the Expression of Uncertainty in Measurement [2].

Unfortunately, the calibration reports for typical deadweight gauge weight sets do not state the correlated and non-correlated uncertainties. Since such correlations typically do exist, and because the non-correlated uncertainties typically are not listed separately, the entire mass uncertainty for each of the same denomination weights is treated as a correlated uncertainty.

These correlated uncertainties are combined using simple summation, rather than root-sum-of-squares. This can result in a rather conservative estimate of the composite mass load uncertainty if significant portions of the component mass uncertainties are actually not correlated. Conversely, if the correlated and uncorrelated mass uncertainties are known, the composite mass load uncertainty can be significantly reduced by combining the uncorrelated mass uncertainties in quadrature with the sum of the correlated uncertainties.

The benefit of this reduction in the composite mass load uncertainty is diminished when it is combined with the uncertainty components for other system influences. If the composite influence from these other influences is relatively high, the benefit of a reduced mass uncertainty is minimal. However, if the composite influence from the other sources is relatively low, the benefit of a reduced mass uncertainty can be rather significant.

Consider a typical laboratory-grade deadweight gauge weight set as an example. The calibration report for this weight set indicates a 5.0 ppm uncertainty in each weight, but does not identify correlated and non-correlated uncertainties. Treating the entire uncertainty in each of the same denomination weights as correlated (as described above) will result in an expanded uncertainty in a composite load of about 5.0 ppm. A more refined analysis of the same mass load, accounting for the correlated and non-correlated uncertainties, might be only 1.8 ppm.

For a deadweight gauge calibration system where the expanded uncertainty is relatively large, the difference between 5.0 ppm and 1.8 ppm for the mass load may be negligible, perhaps less than a 1 percent change in the expanded uncertainty. However, if the expanded uncertainty in the calibration system is relatively low, such that the mass load uncertainty represents a large portion of the component uncertainties, the effect of the refined mass load uncertainty can be much more significant. In one case, a gas deadweight gauge calibration system has an expanded uncertainty of 8.0 ppm using the simpler 5.0 ppm mass load uncertainty. When the mass load uncertainty of 1.8 ppm is used, the expanded uncertainty is reduced to 6.5 ppm—nearly a 20% reduction.

#### Crossfloat System Mass Load Correlations

In a crossfloat calibration system, where two deadweight gauges are compared to each other, it is often the case that the weight sets used on the two gauges are of similar construction—not only having multiple weights of the same denomination within one set, but the same denominations of weights also exist in the other set. If the same-denomination weights in both sets are calibrated using the same mass standard, the correlated errors described above transcend the individual weight sets, and become cross-correlated within the two weight sets (when used in a crossfloat calibration). In the crossfloat system, these cross-correlated errors (and their associated uncertainties) cancel to the extent of the ratio of the effective areas of the two deadweight gauge pistons. Accounting for the cross-correlated weight set errors can significantly reduce the uncertainty in the crossfloat process, however, there are other conditions related to the crossfloat process that can eliminate the need for this evaluation (see "Scatter Influences" below).

The canceling effect of cross-correlated errors is not limited to the mass load. Other sources of cross-correlated errors in the crossfloat process may include portions of the errors related to temperature measurement, thermal coefficients, air buoyancy components, the resolution threshold of the measurement system, and more. Most of these other influences tend to be of lesser impact than the mass load uncertainty, and it is often difficult to identify the cross-correlated uncertainty for these influences. Therefore, it is uncommon that allowances are made in the uncertainty analysis to account for these other cross-correlated influences.

### Scatter Influences

In a typical deadweight gauge crossfloat calibration, numerous combinations of masses are used to build up the various mass loads required to make observations covering the pressure range. Since different combinations of masses are used for the various pressure measurements, errors in the masses typically result in scatter in the residuals of the mathematical fit used to represent the trend in effective area (see reference [1]). In a typical crossfloat analysis, the sample standard deviation of the fit residuals is used to represent the variability in the measurement process. Since the standard deviation represents the net effect of all sources of variability, including the scatter in the results due to errors in the various mass loads, no additional accounting for mass uncertainty is necessary. This condition is not limited to only mass load concerns. Any error source that contributes primarily to the scatter in the results can be accounted for by using the standard deviation to represent the net effect of all such influences.

Numerous ancillary tools and indicators are typically used to facilitate the crossfloat process. The performance and calibration uncertainty of these items affects the overall measurement system uncertainty. The use of these items is generally accompanied by an estimated uncertainty in their indicated value. The uncertainty estimates typically include two key elements—performance of the indicator, and the uncertainty in the calibration of the indicator (primarily, the uncertainty in the parent standard). If the indicators used on the two deadweight gauges are both calibrated using the same parent standard, the resulting cross-correlated errors cancel (as described above in "Crossfloat System Mass Load Correlations"). This leaves essentially only the performance of the indicators as an influence to the crossfloat process. If the performance of the indicators contributes primarily to the scatter in the residuals, it may not be necessary to account for the contribution of the indicator using a separate uncertainty component.

### Historical Archive

Ruska retains its deadweight gauge calibration records for an indefinite period. Some of these records date back to 1955. Examination of these records indicates numerous cases where the deadweight gauges were calibrated several times at Ruska. The archive also includes records of multiple calibrations performed between certain pairs of gauges owned and operated by Ruska. The archive has become an invaluable tool for establishing the long-term stability characteristics.

Even though a deadweight gauge may have very good long-term stability, the true level of stability can be obscured by the variability in the crossfloat process if only a few calibrations

are performed over a relatively short period. Substantiating high long-term stability using a measurement system with variability larger than the long-term stability requires that a large number of measurements be performed over an extended period. Some of the records in the Ruska archive represent pairs of gauges for which a rather large number of comparisons have been performed over periods up to 25 years. These records indicate a long-term stability better than 1 ppm per year.

### Ongoing Efforts

While marked improvements have been recognized in lower pressure gas systems, the uncertainties associated with hydraulic deadweight gauge pressures remain relatively high. The higher operating pressure of the hydraulic deadweight gauge generally results in a higher uncertainty in the pressure-related distortion of the piston/cylinder assembly. The higher pressure is typically associated with the use of smaller diameter pistons (to keep the mass load relatively small). A smaller diameter piston generally results in higher dimensional uncertainty at the fundamental level.

Another factor that increases the uncertainty in hydraulic deadweight gauges is the difficulty in predicting the zero-clearance jacket pressure during the characterization of the controlled-clearance gauges used at the top of the chain. This can result in large changes in the effective area coefficients determined during subsequent characterizations of the fundamental gauge, even though the physical size of the piston and cylinder remain essentially unchanged. If the new coefficients assigned to a fundamental gauge at the top of the chain are significantly different from prior values, it impacts the entire calibration chain. When the new coefficients are passed on to sub-tier gauges, the corresponding changes in the sub-tier gauges might appear as instability. For some conventional laboratory-grade deadweight gauges, the apparent instability can be an order of magnitude larger than the rated stability for that gauge.

Ongoing activities are being focused on improving the uncertainties associated with the hydraulic deadweight gauges. Efforts are being made to improve the reproducibility in the characterization of the fundamental standards and to reduce the uncertainty in the assigned values. Other efforts are aimed at enhancing the data collection process so that more and better data can be collected to identify the fundamental characteristics more accurately.

### Impact on Users

The ever-increasing demand for improved process efficiency increases the demand for more efficient and more accurate production equipment. This demand has prompted development of transducer-based production calibration systems with very high precision and percent of reading performance, such as the Ruska Model 7215xi, rated to 0.005% of reading [3, 4]. Maintaining this new era of high performance production instrumentation also increases the demands for performance and accuracy from the calibration standards.

The latest update to the uncertainty in the Ruska Model 2465 facilitates maintenance of the high-precision production tools while achieving optimal uncertainty. The reduced uncertainty at the standards level leads to lower uncertainties at the production level. Transferring these improvements to the process level benefits the process level in two ways. A reduced

uncertainty yields a more reliable process. It also provides a larger tolerance for other influences. Both of these influences lead to a more efficient and effective process.

## Summary

The recent NIST calibrations of the Ruska Corporate Standards resulted in reduced effective area uncertainties. These reductions have been passed to transfer standards and working standards at Ruska, and can now be transferred to the commercial gauges we calibrate for industry. The refinements to the templates used at Ruska for analyzing the uncertainty in our crossfloat and pressure calibration systems further improve the reliability of the new uncertainty estimates. The improved estimates facilitate the effective transfer of the calibration values from the national standards level, through the various calibration standards, to the process level. These efforts have resulted in a reduction in the expanded uncertainty rating for the Ruska Model 2465 from 15 ppm to 10 ppm. This new capability marks a tenfold reduction in uncertainty in just 10 years and represents a landmark evolutionary step in the availability of high-accuracy pressure measurement capability for commercial industry.

## REFERENCES

[1] Deadweight Pressure Gauges RISP-4, July 1998, 1<sup>st</sup> edition. Boulder, CO: National Conference of Standards Laboratories

[2] Guide to the Expression of Uncertainty in Measurement, 1993, 1<sup>st</sup> edition. Switzerland: International Organization for Standardization (ISO)

[3] Series 7215 - High Speed Digital Pressure Controllers, Document 9908-7215a, Houston, TX: Ruska Instrument Corporation

[4] Pressure Measurement – Precision Test and Measurement Instrumentation, Document 9812-0041, Houston, TX: Ruska Instrument Corporation

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Figure 1. Ruska Low Pressure Gas Deadweight Gauge Traceability Path

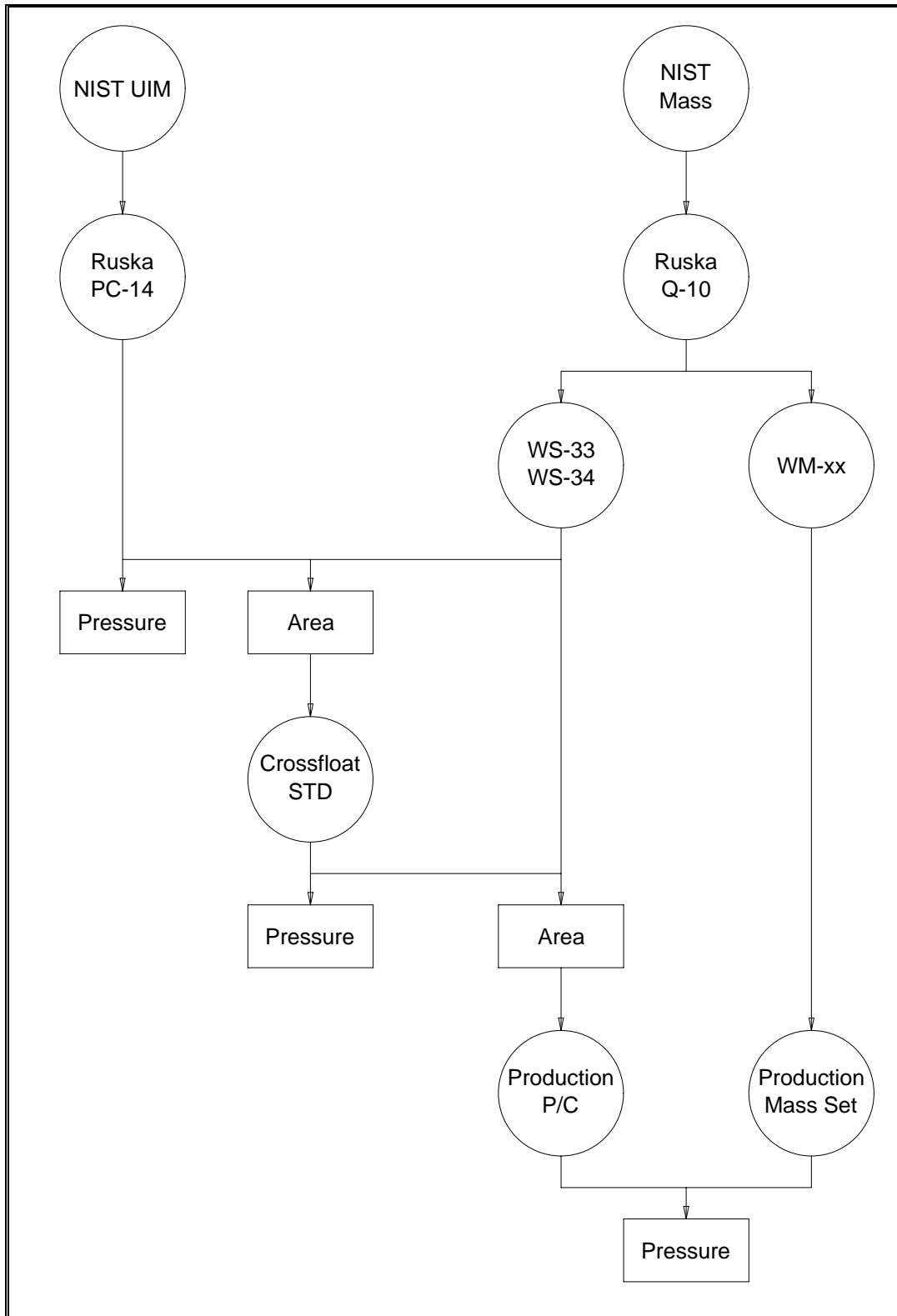


Table 1. Ruska Low Pressure Gas Deadweight Gauge Uncertainty Template

Influence Quantities			Component Uncertainty			Pressure Variant Terms					
Parameter Description	Typical Symbol	Approx. Value	Units	Rectangular Limits (+/-a)	Normal Limits (σ)	Equiv. Std. Unc. (1σ)	Sensitivity Coefficient	Sensitivity Value	Std. Unc. (1σ)	Variance (σ²)	Std. Unc. (σ, ppm)
<b>Effective Area Terms</b>											
Effective Area	A <sub>0</sub>	3.357E-04	m²		1.91E-09	9.57E-10	A <sub>0</sub> <sup>-1</sup>	2.98E+03	2.85E-06	8.12E-12	5.70
Piston Thermal Coef.	α <sub>p</sub>	4.550E-06	°C <sup>-1</sup>	2.28E-07		1.31E-07	T <sub>IND</sub> · T <sub>REF</sub>	-2.00E+00	-2.63E-07	6.90E-14	0.53
Cylinder Thermal Coef.	α <sub>c</sub>	4.550E-06	°C <sup>-1</sup>	2.28E-07		1.31E-07	T <sub>IND</sub> · T <sub>REF</sub>	-2.00E+00	-2.63E-07	6.90E-14	0.53
1 <sup>st</sup> Order Pressure Coef.	b <sub>1</sub>	0.000E+00	P <sub>g</sub> <sup>-1</sup>		0.00E+00	0.00E+00	P · P <sub>IND</sub>	1.72E+05	0.00E+00	0.00E+00	0.00
2 <sup>nd</sup> Order Pressure Coef.	b <sub>2</sub>	0.000E+00	P <sub>g</sub> <sup>-2</sup>		0.00E+00	0.00E+00	(P · P <sub>IND</sub> ) <sup>2</sup>	2.97E+10	0.00E+00	0.00E+00	0.00
Tare Coefficient*	τ	9.559E-11	m²		5.84E-12	2.92E-12	A <sub>0</sub> <sup>-1</sup>	2.98E+03	8.70E-09		0.02
A <sub>0</sub> Stability (2 yrs)	A <sub>0</sub>	3.357E-04	m²		4.48E-10	2.24E-10	A <sub>0</sub> <sup>-1</sup>	2.98E+03	6.67E-07	4.44E-13	1.33
<b>Force Terms</b>											
Mass Load	M	1.182E+01	kg		1.08E-06	5.42E-07	M <sup>1</sup>	8.46E-02	4.58E-08	2.10E-15	0.09
Mass Stability (2 yrs)	M	1.182E+01	kg		7.89E-06	3.94E-06	M <sup>1</sup>	8.46E-02	3.34E-07	1.11E-13	0.67
Local Gravity	g <sub>L</sub>	9.793E+00	m/sec²	1.00E-06	1.50E-06	9.46E-07	g <sub>L</sub> <sup>-1</sup>	1.02E-01	9.67E-08	9.34E-15	0.19
Air Density	ρ <sub>AIR</sub>	1.200E+00	kg/m³		1.61E-03	8.05E-04	ρ <sub>AIR</sub> <sup>-1</sup>	1.28E-04	1.03E-07	1.07E-14	0.21
Mass Load Density	ρ <sub>M</sub>	7.800E+03	kg/m³	2.00E+01	2.00E+00	1.16E+01	ρ <sub>M</sub> / ρ <sub>AIR</sub>	1.97E-08	2.29E-07	5.23E-14	0.46
Verticality (<0.5 deg.)	θ	0.000E+00	deg.		2.00E-02	1.00E-02	1.52306E-04θ	1.52E-06	1.52E-08	2.32E-16	0.03
<b>System Terms</b>											
Indicated Temperature	T <sub>IND</sub>	2.100E+01	°C	1.41E-01		8.16E-02	α <sub>p</sub> + α <sub>c</sub>	9.10E-06	7.43E-07	5.52E-13	1.49
Density of Fluid	ρ <sub>FLUID</sub>	5.129E+00	kg/m³	1.54E-01		8.88E-02	A <sub>0</sub> h/M	0.00E+00	0.00E+00	0.00E+00	0.00
Fluid Head Height	h	0.000E+00	m		5.08E-04	2.54E-04	A <sub>0</sub> (ρ <sub>FLUID</sub> -ρ <sub>AIR</sub> )M	1.12E-04	2.89E-08	8.03E-16	0.06
Float Position	f <sub>PI</sub>	0.000E+00	m		2.54E-04	1.27E-04	A <sub>0</sub> (ρ <sub>FLUID</sub> -ρ <sub>AIR</sub> )M	1.12E-04	1.42E-08	2.01E-16	0.03
Reference Pressure	P <sub>REF</sub>	0.000E+00	Pa		0.00E+00	0.00E+00	P <sup>1</sup>	2.90E-06	0.00E+00	0.00E+00	0.00
Type A Uncertainty	σ	3.357E-04	m²		3.36E-10	1.68E-10	A <sub>0</sub> <sup>-1</sup>	2.98E+03	5.00E-07	2.50E-13	1.00
Piston/Cylinder: PC-14 (TTL-368)						*Uncertainty in Tare coefficient is an additive term.					
Masses: WS-33/WS-34 (98083/20004)						Combined Variance:					
Operating Pressure: 344.9 kPa (gauge mode, nitrogen)						Combined Uncertainty (k=1):					
						<b>Expanded Uncertainty (k=2):</b>					