Fluke Calibration Web Seminar Series

Principles and practical tips about electrical, flow, pressure, RF and temperature calibration

How to Perform an Uncertainty Analysis on Piston Gauges

Presenter: Mike Bair
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Objectives of Webinar

- Get a good idea of what it takes to perform an uncertainty analysis on a Piston Gauge standard.
  - Complete uncertainty analysis training can take much longer than 1 hour. It is assumed that this audience knows at least a little about calculating uncertainty.
  - Piston Gauge uncertainty analysis is complicated. Again 1 hour is not enough time to complete it, but it is enough time to review the essentials.



Objectives of Webinar

- Review a spreadsheet tool used for performing an uncertainty analysis.
  - This will be sent to you when we send the video at the end of the webinar. There are no macros in the spreadsheet tool so it is safe.
  - All functions of the spreadsheet will be explained. Comments are included on the entry cells to help you in the future.
  - Spreadsheet includes control charts for effective area and piston mass. Some explanation of these will be given.

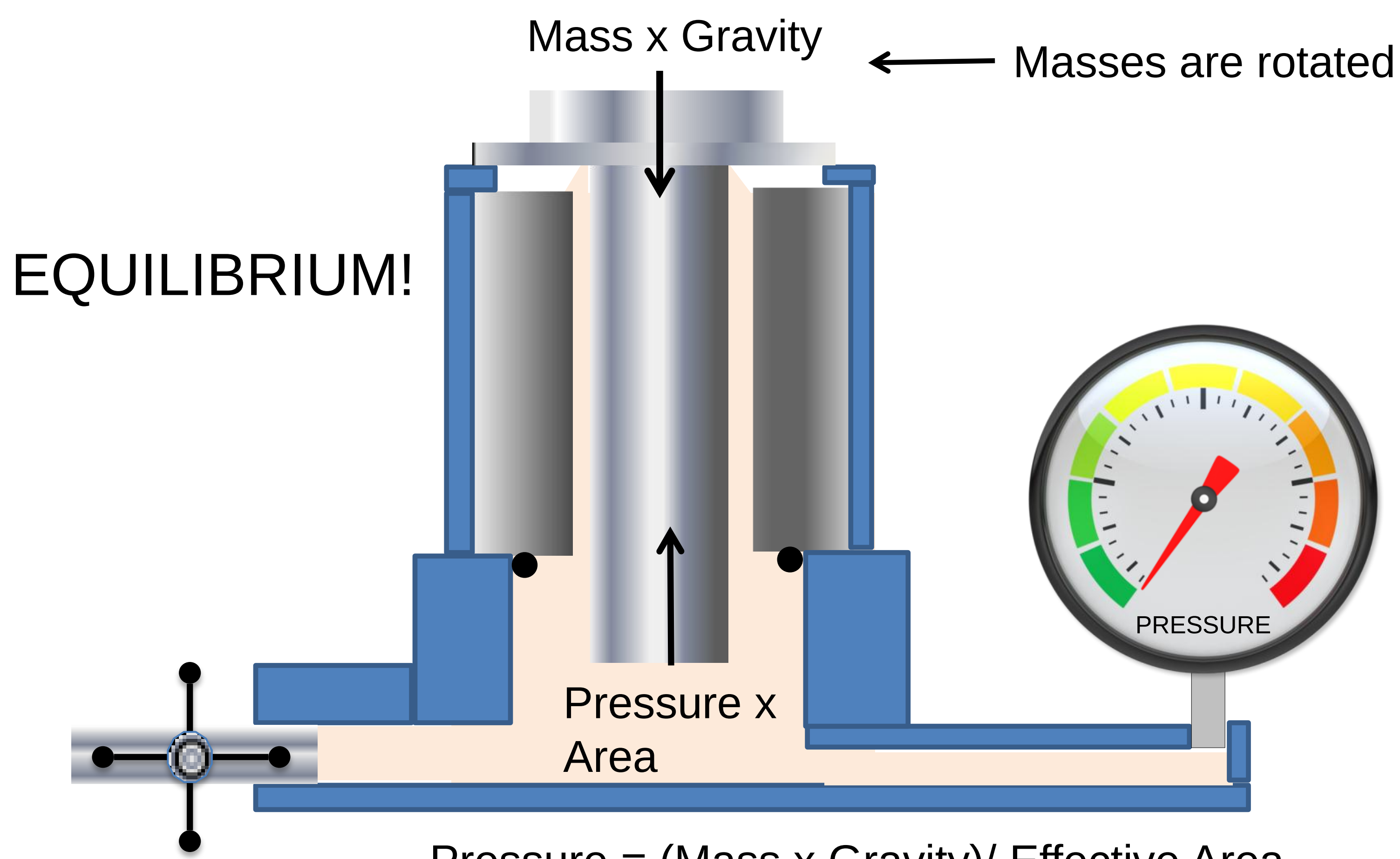
Uncertainty Analysis

- Not going through complete fundamentals of uncertainty analysis.
- If you know very little about uncertainty analysis, please don't leave the webinar.
- You can always review uncertainty analysis fundamentals by playing Jeff Gust's webinar on uncertainty analysis fundamentals, then review this webinar later:
  - http://us.flukecal.com/training/web-seminars/On-demand

Uncertainty Analysis

- But just as a quick review the steps for an analysis are as follows.
  - Determine all influences of uncertainty and their uncertainty, list them as type A or type B
  - Based on their probability distribution and confidence reduce them to a standard uncertainty (1 sigma, k=1)
  - Determine the sensitivity of these standard uncertainties to final measurand. (for example an input in ambient temperature means what in pressure)
  - Express all the standard uncertainties as the final measurand by multiplying them by the sensitivity
  - Accounting for correlations between uncertainties combine them into one value (this is where everyone just RSS's the list)
  - Expand the combined uncertainty to a desired confidence level.

Piston Gauge Uncertainties



Pressure = (Mass x Gravity)/ Effective Area

Piston Gauge Uncertainties

- Sources of uncertainties for Piston Gauges.
  - The most immediate source are the variables in the pressure equation used to calculate pressure (for gauge mode):

$$P = \frac{M \cdot g_L \left(1 - \rho_{air} / \rho_{mass}\right) + \pi D T}{A_{E(Tref,0)}\left[1 + \left(\alpha_p + \alpha_c\right) \cdot \left(T - 20\right)\right]\left(1 + b_1 1 P + b_2 P^2\right)} - \left(\rho_{fluid} - \rho_{air}\right) \cdot g_L \cdot h$$

Piston Gauge Uncertainties

FLUKE Calibration

$$P = \frac{M \cdot g_L \left(1 - \rho_{air} / \rho_{mass}\right) + \pi DT}{A_{E(Tref,0)} \left[1 + \left(\alpha_p + \alpha_c\right) \cdot \left(T - 20\right)\right]\left(1 + b_1 1P + b_2 P^2\right)} - \left(\rho_{fluid} - \rho_{air}\right) \cdot g_L \cdot h$$

Variable	Description
M	Mass load
gl	Local gravity
ρ_{AIR}	Air Density
ρ_{MASS}	Average Density of the mass load
T	Surface tension for hydraulic media
$A_{E(Tref,0)}$	Effective area at reference temperature and 0 pressure
α_P	Thermal expansion of piston
α_C	Thermal expansion of cylinder

Piston Gauge Uncertainties

$$P = \frac{M \cdot g_L \left(1 - \rho_{air} / \rho_{mass}\right) + \pi DT}{A_{E(Tref,0)}\left[1 + (\alpha_p + \alpha_c) \cdot (T - 20)\right]\left(1 + b_1 1P + b_2 P^2\right)} - \left(\rho_{fluid} - \rho_{air}\right) \cdot g_L \cdot h$$

Variable	Description
T	Piston-Cylinder temperature
b_1 or λ	1st order pressure distortion coefficient
b_2	2nd order pressure distortion coefficient
ρ_{FLUID}	Density of the fluid media
h	Pressure head height
P_{REF}	Residual Pressure under bell jar (not shown in the equation)
P_{BARO}	Barometer reading (not shown in the equation)

Piston Gauge Uncertainties

- Other contributions
  - Piston-cylinder sensitivity
  - Piston-cylinder performance (from rotation or piston position)
  - Verticality of the piston-cylinder
  - Linearity
  - Stability

- A review of all influences can be found in three different documents in the “literature and education” link on our website.

Piston Gauge Uncertainties

- Uncertainty Analysis for Pressure Defined by a PG7601, PG7102, PG7202 or PG7302 Piston Gauge
- Typical pressure measurement uncertainty for a PG9607 and PG9602 Piston Gauge Technical Note
- Guide for the uncertainty analysis in pressure when using P3000 Series Deadweight Testers Technical Note

Analysis Considerations

- The ideal state would be a complete analysis for each pressure for measurement uncertainty in a calibration certificate.

- In that case there would be no limits or assumptions, just a calculation based on current conditions.

- Though not completely out of the question, this is very difficult to do and is normally not done.

- Instead an uncertainty analysis for the Piston Gauge is calculated to cover all conditions.

Analysis Considerations

- Limits for the conditions need to be defined in this scenario.
  - What is the worst case temperature correction on the piston-cylinder, i.e. how far from the reference temperature given with the effective area will a correction be made?
  - What modes will the Piston Gauge operate in?
  - What is the largest height for head corrections made?
  - What is the worst case (highest) residual pressure for vacuum?
  - What is worse case air density (lowest) in the air buoyancy correction?

Analysis Considerations

- Some other things to consider are:
  - How do you determine the uncertainty of air density in the air buoyancy correction? How do the instruments used to measure ambient conditions play into it?
  - Uncertainty in air density is included in gauge mode. Uncertainty in the density of mass is included in absolute mode by vacuum.
  - When should we include the uncertainty in elastic deformation (pressure coefficient).

PG Uncertainty Calculation Tool

FLUKE Calibration

- You may have seen this budget in the previously mentioned documents.

Variable or Parameter	Type Unc	Absolute w/ Application of Vacuum	Absolute by/ Addition of Atmospheric Pressure		Gauge	
Full Mass Load -	----------	35 kg	35 kg	55 kg	35 kg	55 kg
(Relative Unc's)	----------	ppm	ppm	ppm	ppm	ppm
Mass (M)	B1	2.50	2.50	2.50	2.50	2.50
Local G	B2	1.00	1.00	1.00	1.00	1.00
Air Density	B3	n/a	0.38	0.38	0.38	0.38
Mass Density	B4	n/a	1.60	1.60	1.60	1.60
Head (height)	B5	0.35	0.35	0.35	0.35	0.35
Head (density)	B6	0.23	0.23	0.23	0.23	0.23
Resolution	B9	0.29	0.29	0.29	0.29	0.29
PC Temp	B10	0.50	0.50	0.50	0.50	0.50
Verticality	B11	0.10	0.10	0.10	0.10	0.10
Effective Area	B12	5.00	5.00	5.00	5.00	5.00
Linearity	B14	0.50	0.50	1.00	0.50	1.00
Elastic Deformation	B15	0.07	0.07	0.11	0.07	0.11
Thermal Expansion	B16	0.22	0.22	0.22	0.22	0.22
Stability Ae	B17	0.50	0.50	0.50	0.50	0.50
Sensitivity	B13	0.14	0.14	0.14	0.14	0.14
Type A	A1	0.50	0.50	0.50	0.50	0.50
COMBINED		5.8 ppm + 0.11 Pa	6.0 ppm + 5.00 Pa	6.1 ppm + 5.00 Pa	6.0 ppm + 0.04 Pa	6.0 ppm + 0.05 Pa
COMBINED & EXPANDED FOR (K=2)		12 ppm + 0.2 Pa	12 ppm + 10 Pa	12 ppm + 10 Pa	12 ppm + 0.07 Pa	12 ppm + 0.09 Pa
(Absolute Unc's)	----------	Pa	Pa	Pa	Pa	Pa
Barometric Pressure	B8	n/a	5.00	5.00	n/a	n/a
Vac	B7	0.1	n/a	n/a	n/a	n/a
Surface Tension	n/a	n/a	n/a	n/a	n/a	n/a
Sensitivity	B13	0.006	0.006	0.006	0.006	0.006
Bell Mass	B1a	0.025	0.025	0.040	0.025	0.040
Piston Mass	B1b	0.025	0.025	0.025	0.025	0.025

PG Uncertainty Calculation Tool

- This is a nice uncertainty budget but there are some criticisms with it.
  - The relative and constant uncertainties are added but they are not necessarily correlated. So it is conservative.
  - Also the analysis is based on k=2 instead of the preferred 95%.
  - It is not a spreadsheet so one must be created with the information given.

Variable or Parameter	Type Unc	Absolute w/ Application of Vacuum	Absolute by Addition of Atmospheric Pressure		Gauge	
Full Mass Load	----------	35 kg	35 kg	55 kg	35 kg	55 kg
(Relative Unc's)	----------	ppm	ppm	ppm	ppm	ppm
Mass (M)	B1	2.50	2.50	2.50	2.50	2.50
Local G	B2	1.00	1.00	1.00	1.00	1.00
Air Density	B3	n/a	0.38	0.38	0.38	0.38
Mass Density	B4	n/a	1.60	1.60	1.60	1.60
Head (height)	B5	0.35	0.35	0.35	0.35	0.35
Head (density)	B6	0.23	0.23	0.23	0.23	0.23
Resolution	B9	0.29	0.29	0.29	0.29	0.29
PC Temp	B10	0.50	0.50	0.50	0.50	0.50
Verticality	B11	0.10	0.10	0.10	0.10	0.10
Effective Area	B12	5.00	5.00	5.00	5.00	5.00
Linearity	B14	0.50	0.50	1.00	0.50	1.00
Elastic Deformation	B15	0.07	0.07	0.11	0.07	0.11
Thermal Expansion	B16	0.22	0.22	0.22	0.22	0.22
Stability Ae	B17	0.50	0.50	0.50	0.50	0.50
Sensitivity	B13	0.14	0.14	0.14	0.14	0.14
Type A	A1	0.50	0.50	0.50	0.50	0.50
COMBINED		5.8 ppm + 0.11 Pa	6.0 ppm + 5.00 Pa	6.1 ppm + 5.00 Pa	6.0 ppm + 0.04 Pa	6.0 ppm + 0.05 Pa
COMBINED & EXPANDED FOR (K=2)		12 ppm + 0.2 Pa	12 ppm + 10 Pa	12 ppm + 10 Pa	12 ppm + 0.07 Pa	12 ppm + 0.09 Pa
(Absolute Unc's)	----------	Pa	Pa	Pa	Pa	Pa
Barometric Pressure	B8	n/a	5.00	5.00	n/a	n/a
Vac	B7	0.1	n/a	n/a	n/a	n/a
Surface Tension	n/a	n/a	n/a	n/a	n/a	n/a
Sensitivity	B13	0.006	0.006	0.006	0.006	0.006
Bell Mass	B1a	0.025	0.025	0.040	0.025	0.040
Piston Mass	B1b	0.025	0.025	0.025	0.025	0.025

PG Uncertainty Calculation Tool

- The following is another budget you may have used provided by Ruska. Relative and constants are evaluated together so is not overly conservative.

Influence Quantities				Component Uncertainty			Pressure Variant Terms				
Parameter Description	Typical Symbol	Approx. Value	Units	Rectangular Limits (+/-a)	Normal Limits (2σ)	Equiv. Std. Unc. (1σ)	Sensitivity Coefficient	Sensitivity Value	Std. Unc. (1σ)	Variance (σ^2)	Std. Unc. (2σ, ppm)
Effective Area Terms											
Effective Area	A_o	8.393E-05	m^2		6.91E-10	3.45E-10	A_o^{-1}	1.19E+04	4.12E-06	1.69E-11	8.23
Piston Thermal Coef.	α_P	4.550E-06	$^oC^{-1}$	2.28E-07		1.31E-07	$T_{IND} - T_{REF}$	-1.00E+00	-1.31E-07	1.73E-14	0.26
Cylinder Thermal Coef.	α_C	4.550E-06	$^oC^{-1}$	2.28E-07		1.31E-07	$T_{IND} - T_{REF}$	-1.00E+00	-1.31E-07	1.73E-14	0.26
1st Order Pressure Coef.	b_1	0.000E+00	Pa^{-1}		0.00E+00	0.00E+00	$P - P_{MID}$	6.99E+05	0.00E+00	0.00E+00	0.00
2nd Order Pressure Coef.	b_2	0.000E+00	Pa^{-2}		0.00E+00	0.00E+00	$(P - P_{MID})^2$	4.88E+11	0.00E+00	0.00E+00	0.00
Tare Coefficient*	τ	0.000E+00	m^2		0.00E+00	0.00E+00	A_o^{-1}	1.19E+04	0.00E+00		0.00
A_o Stability (2 yrs)	A_o	8.393E-05	m^2		1.12E-10	5.59E-11	A_o^{-1}	1.19E+04	6.67E-07	4.44E-13	1.33
Force Terms											
Mass Load	M	1.198E+01	kg		1.69E-05	8.45E-06	M^{-1}	8.35E-02	7.05E-07	4.97E-13	1.41
Mass Stability (2 yrs)	M	1.198E+01	kg		7.99E-06	3.99E-06	M^{-1}	8.35E-02	3.34E-07	1.11E-13	0.67
Local Gravity	g_L	9.793E+00	m/sec^2		9.79E-06	4.90E-06	g_L^{-1}	1.02E-01	5.00E-07	2.50E-13	1.00
Air Density	ρ_{AIR}	1.200E+00	kg/m^3		7.00E-03	3.50E-03	ρ_M^{-1}	1.28E-04	4.49E-07	2.01E-13	0.90
Mass Load Density	ρ_M	7.800E+03	kg/m^3	2.00E+01	2.00E+00	1.16E+01	ρ_{AIR}/ρ_M^2	1.97E-08	2.29E-07	5.23E-14	0.46
Verticality (<0.5 deg.)	θ	0.000E+00	deg.	5.00E-02	5.00E-02	3.82E-02	1.52308E-04θ	5.82E-06	2.22E-07	4.93E-14	0.44
System Terms											
Indicated Temperature	T_{IND}	2.200E+01	^oC	1.41E-01		8.16E-02	$\alpha_P + \alpha_C$	9.10E-06	7.43E-07	5.52E-13	1.49
Density of Fluid	ρ_{FLUID}	1.723E+01	kg/m^3	5.17E-01		2.98E-01	$A_o h/M$	0.00E+00	0.00E+00	0.00E+00	0.00
Fluid Head Height	h	0.000E+00	m		5.08E-03	2.54E-03	$A_o(\rho_{FLUID}-\rho_{AIR})/M$	1.12E-04	2.85E-07	8.14E-14	0.57
Float Position	fpi	0.000E+00	m		2.54E-04	1.27E-04	$A_o(\rho_{FLUID}-\rho_{AIR})/M$	1.12E-04	1.43E-08	2.03E-16	0.03
Reference Pressure	P_{REF}	0.000E+00	Pa		0.00E+00	0.00E+00	P^{-1}	7.15E-07	0.00E+00	0.00E+00	0.00
Type A Unc. (typical)	σ	8.393E-05	m^2		1.68E-10	8.39E-11	A_o^{-1}	1.19E+04	1.00E-06	1.00E-12	2.00
Piston/Cylinder: C-xxx			*Uncertainty in Tare coefficient is an additive term.						Combined Variance:	2.02E-11	
Masses: 2468-799/2465-799									Combined Uncertainty (k=1):	4.50E-06	
Operating Pressure: 1397.8 kPa (gauge mode, nitorgen)									**Expanded Uncertainty (k=2):**	**9.0 ppm**	

Analysis Considerations

- Also a nice budget but can also be criticized.
  - The spreadsheet is for a single pressure.
  - No limits are given since it is for a single pressure.
  - Also does not use 95% but k=2.
  - Very manual, requires user analysis of mode and media.

Influence Quantities				Component Uncertainty			Pressure Variant Terms				
Parameter Description	Typical Symbol	Approx. Value	Units	Rectangular Limits (+/-a)	Normal Limits (2σ)	Equiv. Std. Unc. (1σ)	Sensitivity Coefficient	Sensitivity Value	Std. Unc. (1σ)	Variance (σ^2)	Std. Unc. (2σ, ppm)
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1st Order Pressure Coef.	b_1	0.000E+00	Pa^{-1}		0.00E+00	0.00E+00	$P - P_{MID}$	6.99E+05	0.00E+00	0.00E+00	0.00
2nd Order Pressure Coef.	b_2	0.000E+00	Pa^{-2}		0.00E+00	0.00E+00	$(P - P_{MID})^2$	4.88E+11	0.00E+00	0.00E+00	0.00
Tare Coefficient*	τ	0.000E+00	m^2		0.00E+00	0.00E+00	A_o^{-1}	1.19E+04	0.00E+00		0.00
A_o Stability (2 yrs)	A_o	8.393E-05	m^2		1.12E-10	5.59E-11	A_o^{-1}	1.19E+04	6.67E-07	4.44E-13	1.33
Force Terms											
Mass Load	M	1.198E+01	kg		1.69E-05	8.45E-06	M^{-1}	8.35E-02	7.05E-07	4.97E-13	1.41
Mass Stability (2 yrs)	M	1.198E+01	kg		7.99E-06	3.99E-06	M^{-1}	8.35E-02	3.34E-07	1.11E-13	0.67
Local Gravity	g_L	9.793E+00	m/sec^2		9.79E-06	4.90E-06	g_L^{-1}	1.02E-01	5.00E-07	2.50E-13	1.00
Air Density	ρ_{AIR}	1.200E+00	kg/m^3		7.00E-03	3.50E-03	ρ_M^{-1}	1.28E-04	4.49E-07	2.01E-13	0.90
Mass Load Density	ρ_M	7.800E+03	kg/m^3	2.00E+01	2.00E+00	1.16E+01	ρ_{AIR}/ρ_M^2	1.97E-08	2.29E-07	5.23E-14	0.46
Verticality (<0.5 deg.)	θ	0.000E+00	deg.	5.00E-02	5.00E-02	3.82E-02	1.52308E-04θ	5.82E-06	2.22E-07	4.93E-14	0.44
System Terms											
Indicated Temperature	T_{IND}	2.200E+01	^oC	1.41E-01		8.16E-02	$\alpha_P + \alpha_C$	9.10E-06	7.43E-07	5.52E-13	1.49
Density of Fluid	ρ_{FLUID}	1.723E+01	kg/m^3	5.17E-01		2.98E-01	$A_o h/M$	0.00E+00	0.00E+00	0.00E+00	0.00
Fluid Head Height	h	0.000E+00	m		5.08E-03	2.54E-03	$A_o(\rho_{FLUID}-\rho_{AIR})/M$	1.12E-04	2.85E-07	8.14E-14	0.57
Float Position	fpi	0.000E+00	m		2.54E-04	1.27E-04	$A_o(\rho_{FLUID}-\rho_{AIR})/M$	1.12E-04	1.43E-08	2.03E-16	0.03
Reference Pressure	P_{REF}	0.000E+00	Pa		0.00E+00	0.00E+00	P^{-1}	7.15E-07	0.00E+00	0.00E+00	0.00
Type A Unc. (typical)	σ	8.393E-05	m^2		1.68E-10	8.39E-11	A_o^{-1}	1.19E+04	1.00E-06	1.00E-12	2.00
Piston/Cylinder: C-xxx			*Uncertainty in Tare coefficient is an additive term.						Combined Variance:	2.02E-11	
Masses: 2468-799/2465-799									Combined Uncertainty (k=1):	4.50E-06	
Operating Pressure: 1397.8 kPa (gauge mode, nitorgen)									**Expanded Uncertainty (k=2):**	**9.0 ppm**	

PG Uncertainty Calculation Tool

- The following is a demonstration of the PG uncertainty calculation tool.
  - Is primarily based on the Ruska spreadsheet but expanded and automated to help reduce the amount of time evaluating.
  - Calculates an uncertainty for a range of pressures.
  - Includes comments as guidance in the evaluation.
  - Provides control charts for effective area and mass.
  - Is intended to be improved in the future.

PG Uncertainty Calculation Tool

- Improvements to follow with this tool?
  - Use of correlation where needed.
  - Include Differential Mode.
  - Better control charting for the mass set.
  - Simultaneous calculation of uncertainty for all modes.
  - Unknown issues or undesirable features that you tell me about.

PG Uncertainty Calculation Tool

- For questions complaints, complements please contact myself at:

mike.bair@flukecal.com

602 773 4734

  - **Thanks for joining us today.** One favor I have. Please do not contact out technical support department or customer care center regarding the spreadsheet as they do not have the knowledge on this spreadsheet to answer your questions…. Speaking of which…

QUESTIONS ANYONE?

Future web seminars

Temperature Calibration seminars coming soon:

- October 8: Annealing an RTD: Why, When, and How (presented in English)
- October 22: Annealing an RTD: Why, When, and How (presented in Spanish)
- November 12: Understanding Uncertainties Associated with Dry-block Calibrators (presented in English)

For the latest schedule visit

www.flukecal.com/calwebsem

Our seminar topics cover principles and practical tips about electrical, flow, pressure, RF and temperature calibration

Thank you

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