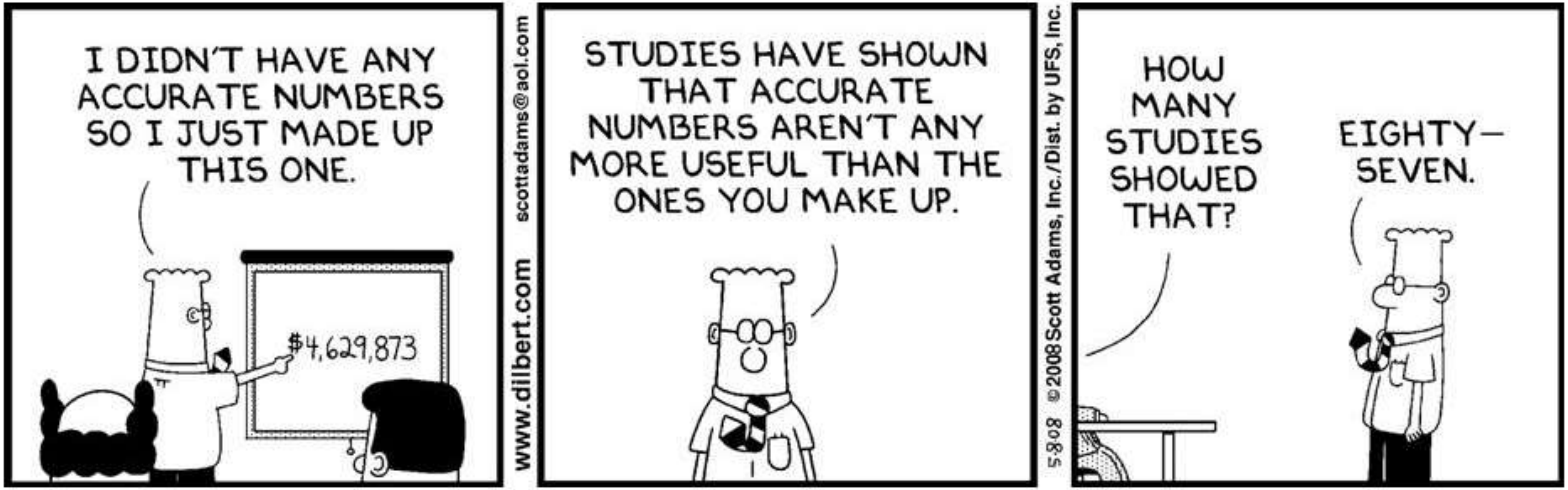
Garbage In = Garbage Out (GIGO)

Understanding the Effects of Uncertainty

Brian Wodka
RMF Engineering
IDEA CampusEnergy 2019 – New Orleans, LA



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“Garbage in equals garbage out.”

‘Your analysis is only as good as your data.’

So… how good *is* your data?

What is the value of your analysis?

How impactful is your data/analysis on decisions?

Definition of "Uncertainty"

"The lack of being certain."

- Merriam-Webster

"Measurement Uncertainty"

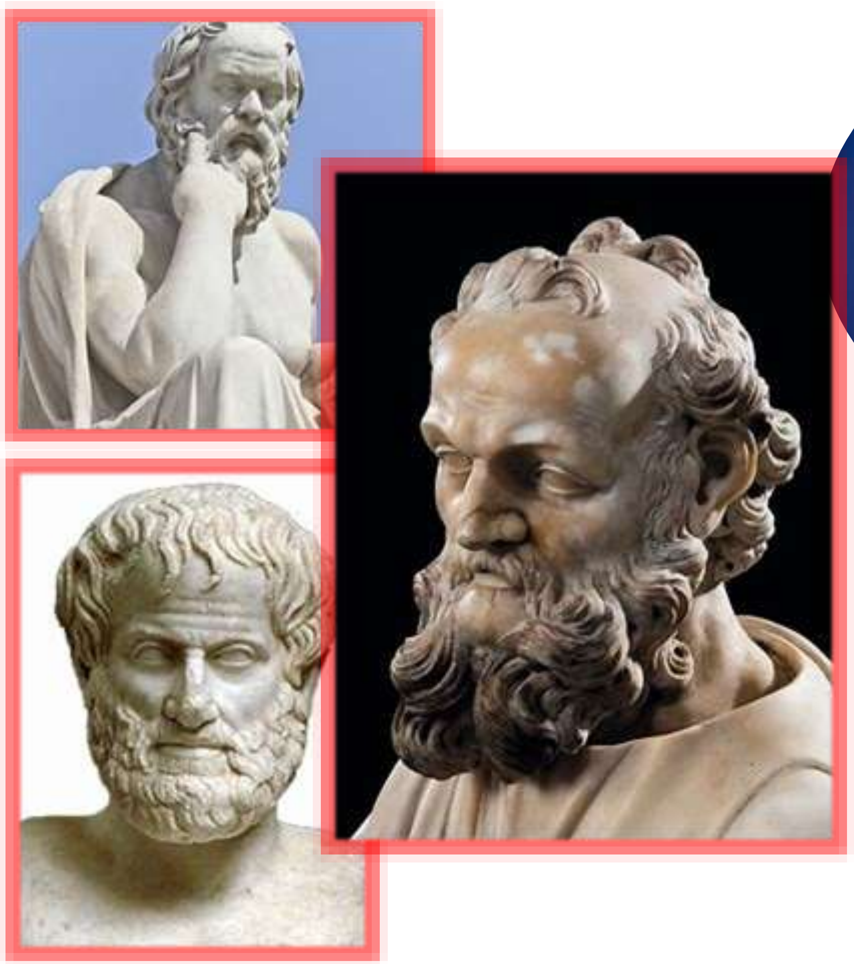
A "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used."

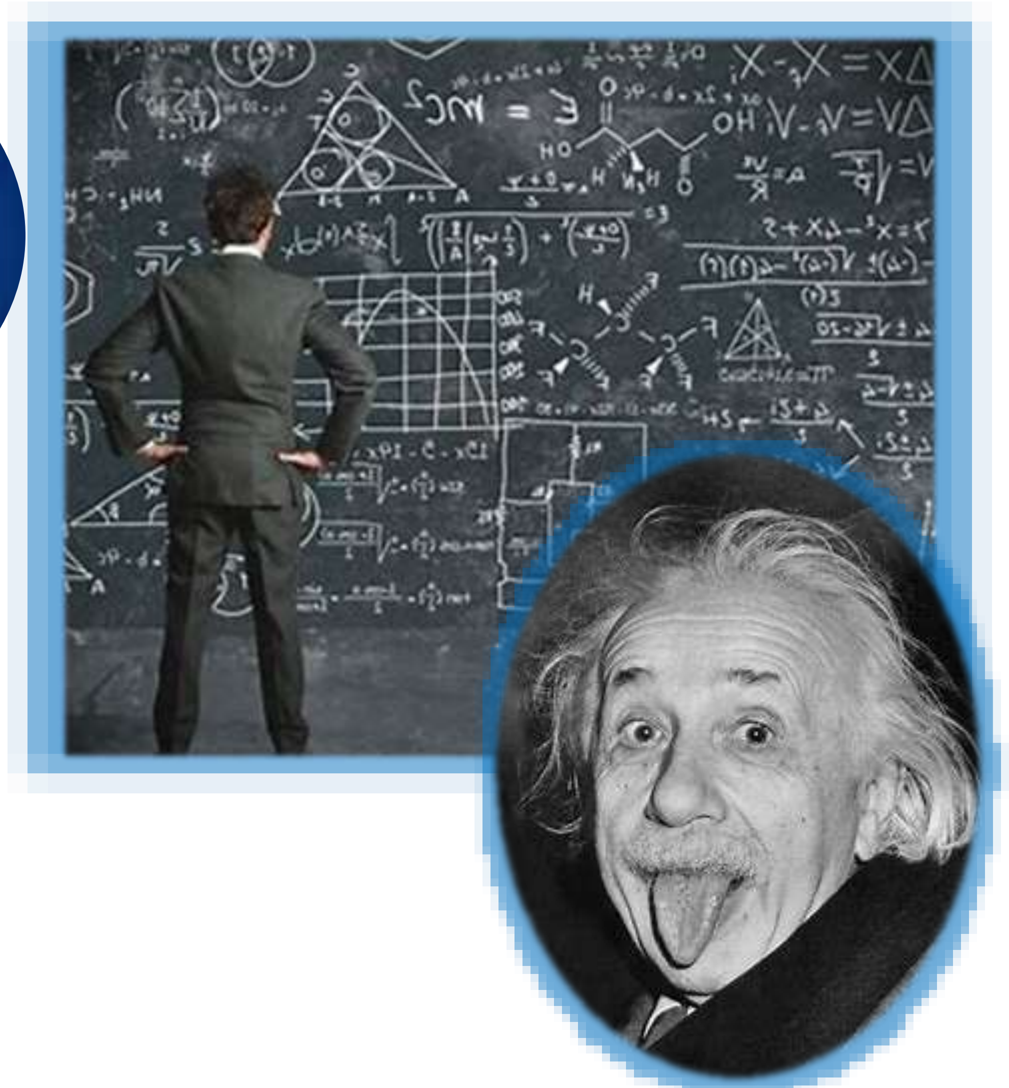
- JCGM 200:2008 (VIM), definition 2.26

Measurement Uncertainty

- Addresses the inevitable error inherent in all measurements.
- Do not define “error” as “mistake”, but instead as a known ‘variance’.
- The difference between an observed or calculated value and a true value.
- *It is used as a measure of the quality of a test.*

The Uncertainty of Uncertainty





The TRUTH

...is out there.

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The Uncertainty of Uncertainty

- “**Uncertainty itself is uncertain, therefore, you cannot evaluate it exactly.**”
  - Milivoje Kostic, professor of mechanical engineering, Northern Illinois University
- “**Calibration is not perfect because you’re only comparing your instrument with something that is a little better.**”
  - W. Glenn Steele, distinguished professor of mechanical engineering, Mississippi State University
- **“Essentially, all models are wrong, but some are useful.”**
  - George E. P. Box
- **“Uncertainty is the science of accuracy of the inaccuracy of science.”**
  - Me

Accuracy and Precision

Accuracy

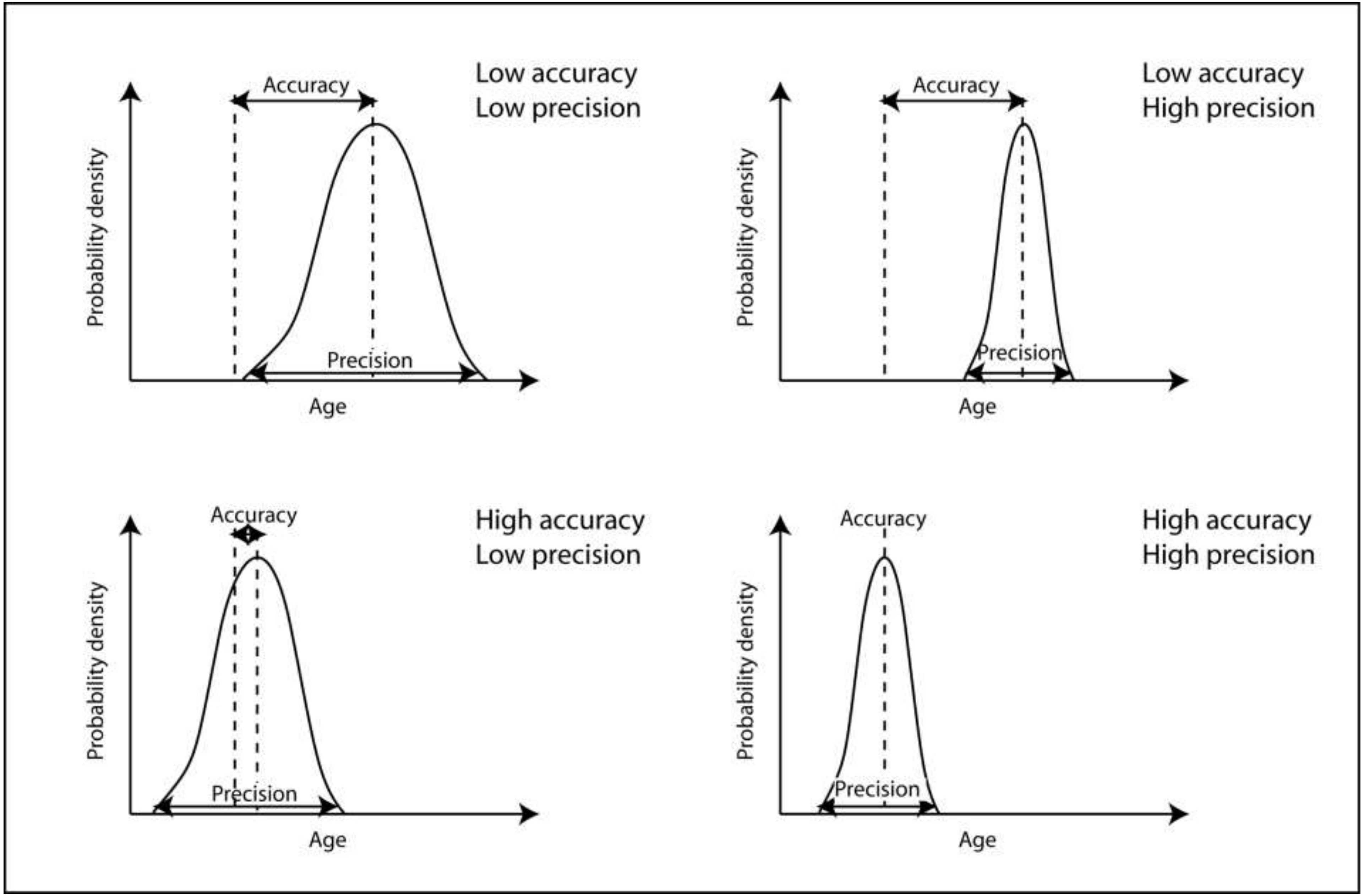
How close a measurement is to the true value

Accuracy Error: *Systematic error, Bias*

Precision

Magnitude of variation in a set of measurements

Precision Error: *Random error, Scatter*


Low accuracy
Low precision
Accuracy
Precision
Probability density
Age
Low accuracy
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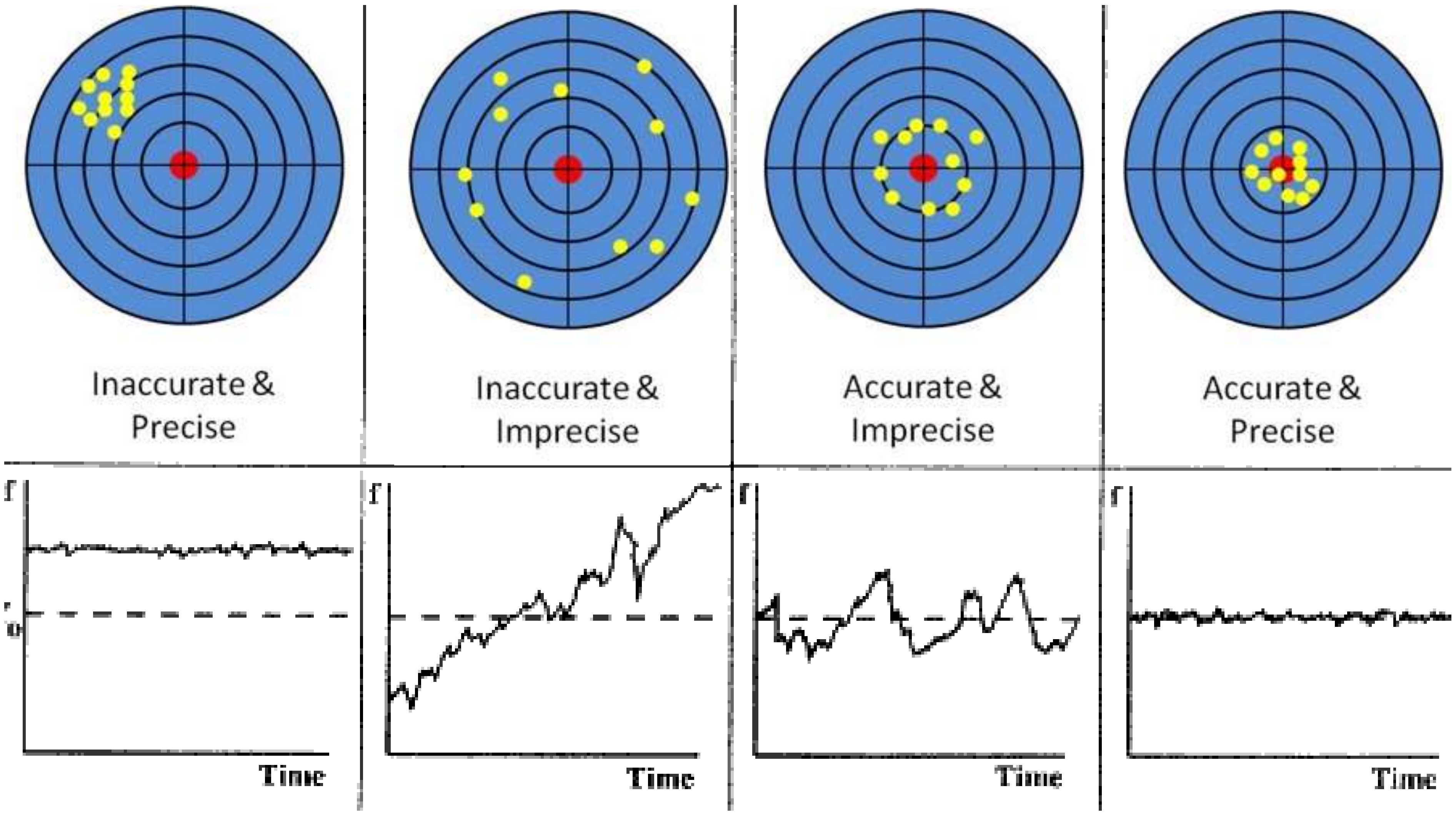
Accuracy and Precision



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Uncertainty Analysis Process

1. **Define the Measurement Process**
   Identify the Objectives, Calculations, Parameters, Calibrations, Functional Relationships
2. **List Elemental Error Sources**
   Brainstorm all potential sources of error for each component
3. **Calculate Systematic and Random Uncertainty**
   From empirical data or other sources
4. **Propagate Standard Deviations**
   Establish probability curves
5. **Data Reduction**
   Make any necessary adjustments/corrections
6. **Calculate Total Uncertainty**
   Combine and expand

So What Does This Mean To Me?...

- How do I know if what I already have is good enough?
- When should I care and require low uncertainty?
- How sensitive is uncertainty on the measurement of interest?
- What is the point of diminishing returns?

ASHRAE

"Test results should *never* be reported without also reporting their measurement uncertainty. No manager or process owner should take action based on the test results with an undefined measurement uncertainty."

- Dieck (1992)

You Should Care!

Because...*Garbage In = Garbage Out!*

- ✓ **Performance testing (yes)**
- ✓ **High value decisions (yes)**
- ❖ **Day-to-day operations (not so much)**

Measurement, *tolerance*, confidence

124,582 PPH

+/- 1,000 PPH

95% confidence (k=2)

Uncertainty is the culmination of both *Systematic* and *Random* Uncertainties.

Sources of Uncertainty

Systematic Uncertainty

- Incorrect Installation
- Calibration Error
- Instrument Drift
- Hysteresis
- Flow Stratification
- Environmental Factors
- Electrical Noise

Random Uncertainty

- Instrument Quality
- System Stability
- Environmental Factors

Some Typical Uncertainties

- **Efficiency**:

  Packaged Boiler (w/economizer)
  - Energy Balance Method
    - 0.2 – 0.5% (gas)
    - 0.3 – 0.6% (oil)
  - Input-Output Method
    - 1.2% (gas or oil)

- **Heat Rate**
  - Solid Fuel: <3.0%
  - All others: <1.5%
- **Power**
  - All: <1.0%

Power Plant Example

- Efficiency (Input-Output Method)

$$\eta = \frac{Energy_{\ out}}{Energy_{\ in}} \text{ x } 100$$

$$\eta = \frac{BTU_{Steam} - BTU_{Feedwater}}{BTU_{Fuel}} \text{ x } 100$$

$$\eta = \frac{(\boldsymbol{PPH_{Steam}} * \ h_{g,steam}) - (\boldsymbol{PPH_{Feedwater}} * \ h_{f,feedwater})}{\boldsymbol{kcfh} * \ HHV}$$

Power Plant Example

Characteristics	Units	Min Fire	25%	50%	75%	100%
Boiler Master Out	%	12.5	26	50	75	100
Capacity (Steam Flow)	kPPH	26.2	41.5	79.6	116.8	156.7
Outlet Pressure	psig	208.1	207.3	220.7	197.4	225.8
Drum Temperature	F	395	395.4	402.8	399.7	413.8
Drum Pressure	psig	219.1	219.7	240.2	231.6	273.8
Superheat Temperature	F	435.4	451.7	452.7	437.3	440.1
Fuel Flow (NG)	kCFH	23.2	46.1	92.5	138.6	184.4
Fuel Cv Position (Main)	% open	9.00	19.3	36.1	51.3	77.7
Gas Supply Pressure	psig	14.9	15	14.6	14.5	14.3
Main Flame Scanner	-	76	86.8	87	86.8	87
Feedwater Flow	kPPH	19.4	46	73.4	112	148.1
Feedwater Cv Position	% open	10.8	24	40.8	51.5	76.1
FW Entering Econo	F	228	228.5	229	229.2	229.1
FW Exiting Econo	F	252.2	244	249.1	263.2	279.5

Efficiency = 81.4%

Power Plant Example

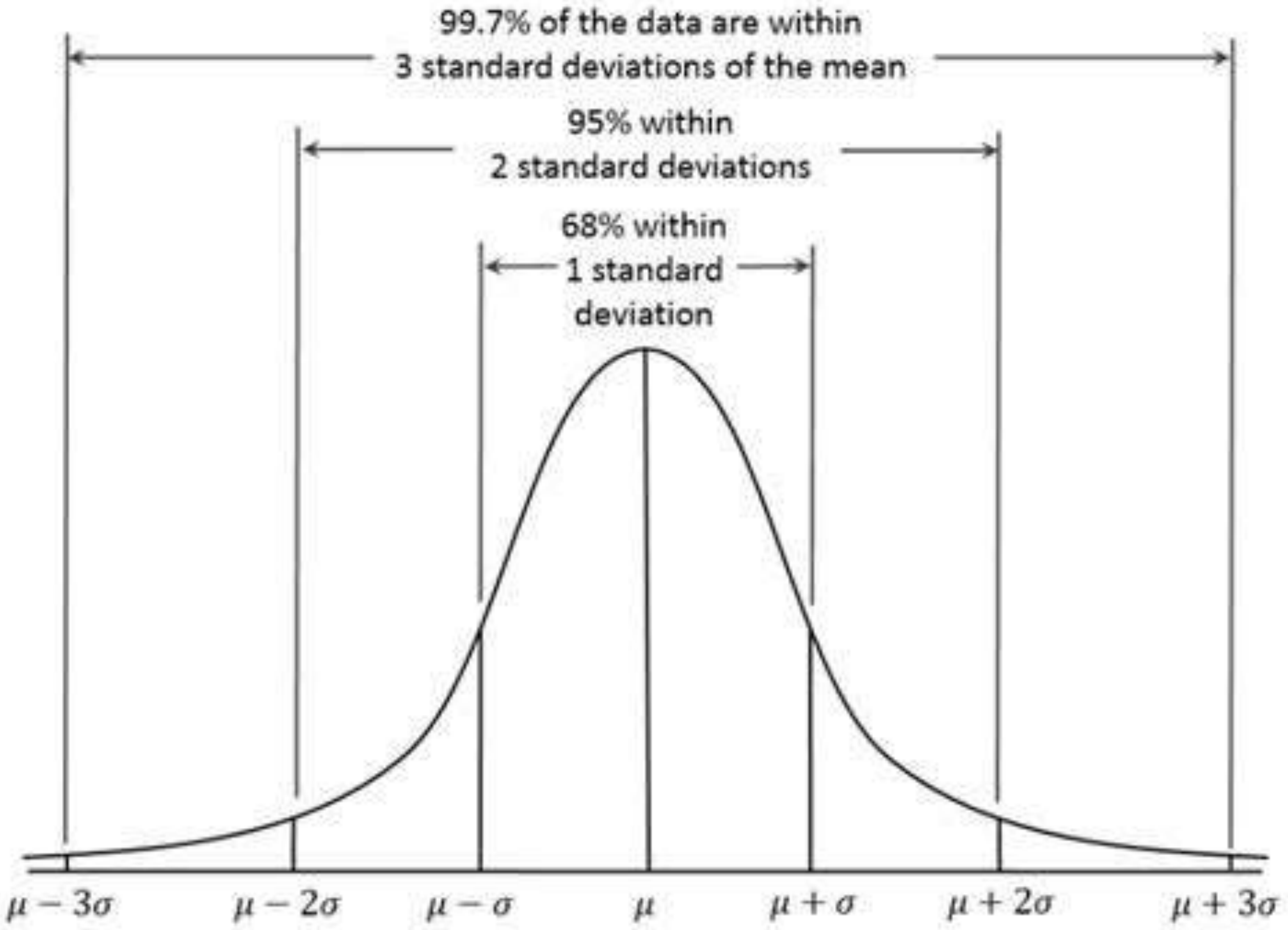
Uncertainty				
Systematic	Random	θ	Systematic Contribution	Random Contribution
0.50	0.310	1.027	0.263682	0.101359
0.25	0.500	0	0	0
0.18	-1.100	0	0	0
0.25	-0.750	0	0	0
0.18	1.300	0.217	0.001526	0.07958
2.00	0.092	-0.787	2.477476	0.005242
0.50	-0.300	0	0	0
0.25	0.000	0	0	0
0.20	-0.250	0	0	0
2.00	2.600	-0.182	0.132496	0.223918
0.50	0.200	0	0	0
0.13	0.030	0	0	0
0.13	0.060	-0.228	0.000879	0.000187
			2.49499	0.258406
	Combined	2.508336	U_R Expanded	+/- 5.02% $U_{R,95}$

Power Plant Example

Uncertainty				
Systematic	Random	θ	Systematic Contribution	Random Contribution
0.50	0.310	1.027	0.263682	0.101359
0.25	0.500	0	0	0
0.18	-1.100	0	0	0
0.25	-0.750	0	0	0
0.18	1.300	0.217	0.001526	0.07958
0.50	0.092	-0.787	0.154842	0.005242
0.50	-0.300	0	0	0
0.25	0.000	0	0	0
0.20	-0.250	0	0	0
2.00	2.600	-0.182	0.132496	0.223918
0.50	0.200	0	0	0
0.13	0.030	0	0	0
0.13	0.060	-0.228	0.000879	0.000187
			0.333261	0.258406
	Combined	0.421707	U_R Expanded	+/- 0.84% $U_{R,95}$

Power Plant Example

Uncertainty				
Systematic	Random	θ	Systematic Contribution	Random Contribution
0.50	0.310	1.027	0.263682	0.101359
0.25	0.500	0	0	0
0.18	-1.100	0	0	0
0.25	-0.750	0	0	0
0.18	1.300	0.217	0.001526	0.07958
0.50	0.092	-0.787	0.154842	0.005242
0.50	-0.300	0	0	0
0.25	0.000	0	0	0
0.20	-0.250	0	0	0
0.50	2.600	-0.182	0.008281	0.223918
0.50	0.200	0	0	0
0.13	0.030	0	0	0
0.13	0.060	-0.228	0.000879	0.000187
			0.305902	0.258406
	Combined	0.400437	U_R Expanded	+/- 0.80% $U_{R,95}$


99.7% of the data are within
3 standard deviations of the mean
95% within
2 standard deviations
68% within
1 standard
deviation
μ − 3σ
μ − 2σ
μ − σ
μ
μ + σ
μ + 2σ
μ + 3σ

Calculating Uncertainty

POWER

- Fundamental: $\boldsymbol{P_{corr} = \left(P_{meas} + \sum_{i=1}^{7} \Delta_i\right) \prod_{j=1}^{5} \alpha_j}$

- Specific: $P_{corr} = (P_{meas} + \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4)\, \alpha_1 \alpha_2 \alpha_3$

HEAT RATE

- Fundamental: $\boldsymbol{HR_{corr} = \frac{\left(Q_{meas} + \sum_{i=1}^{7} \omega_i\right) \prod_{j=1}^{5} \beta_j}{\left(P_{meas} + \sum_{i=1}^{7} \Delta_i\right) \prod_{j=1}^{5} \alpha_j}}$

- Specific: $HR_{corr} = \frac{(Q_{meas})\, \beta_1 \beta_2 \beta_3}{(P_{meas} + \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4)\, \alpha_1 \alpha_2 \alpha_3}$

Calculating Uncertainty

$$\frac{\boldsymbol{U_{HR_{corr}}}}{\boldsymbol{HR_{corr}}} = \left[\frac{U_{Q_{meas}}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial Q_{meas}}\right)^2 + \frac{U_{P_{meas}}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial P_{meas}}\right)^2 + \frac{U_{m_{therm}}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial m_{therm}}\right)^2 + \frac{U_{pf}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial pf}\right)^2 + \frac{U_{T_{inl}}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial T_{inl}}\right)^2 + \frac{U_{P_{amb}}^2}{HR_{corr}^2}\left(\frac{\partial HR_{corr}}{\partial P_{amb}}\right)^2\right.$$

FUN! FUN! FUN!

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Metrological Traceability

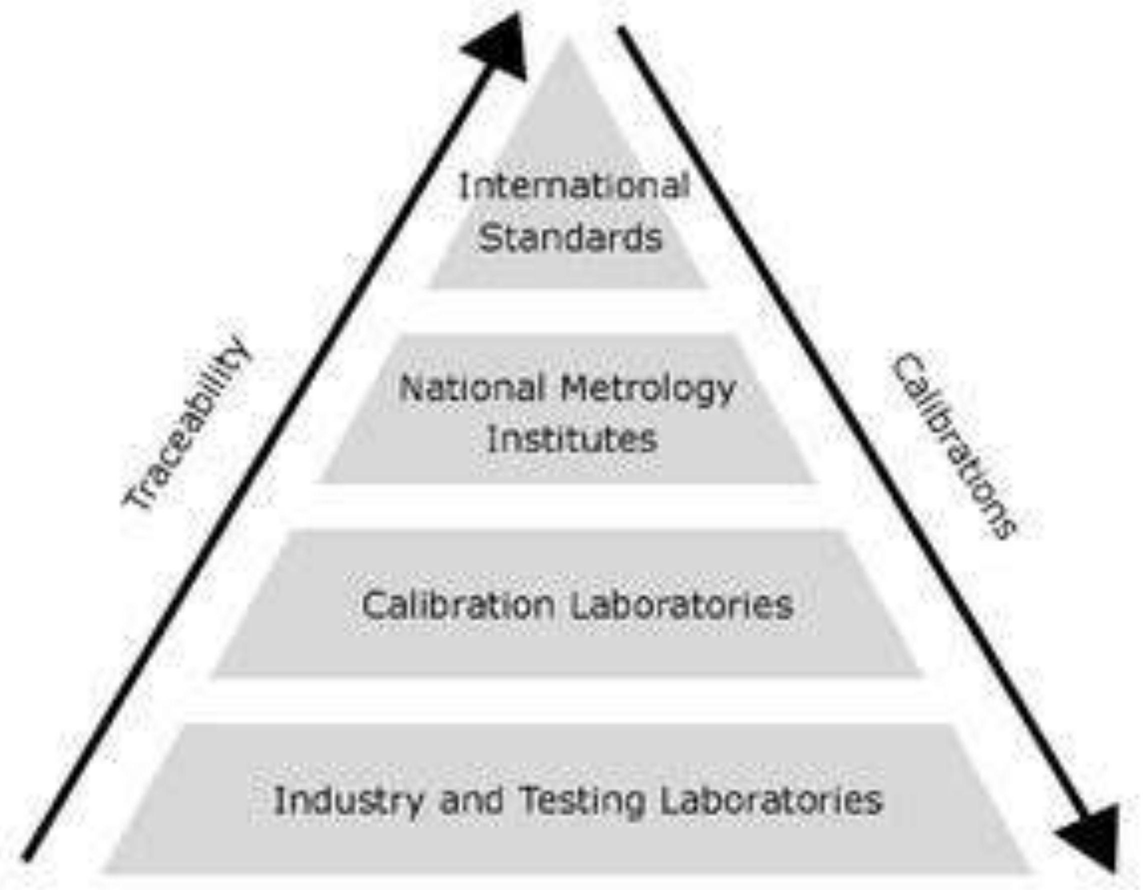
"Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."

International Vocabulary of Metrology

Basic and General Concepts and Associated Terms, definition 2.41

Traceability

- **“NIST Traceability”**
- **Certificate of Traceability**



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Conclusion

- **Be aware of Measurement Uncertainty.**
- **Identify where you could be exposed to uncertainty.**
- **Know how and when to control it.**

Brian Wodka, PE, CxA, CEM, LEED AP

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References:

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ASME PTC 19.2 “Test Uncertainty”

ASME PTC 46 “Overall Plant Performance”

JCGM 200:2008 “Vocabulaire International de Metrologie” (VIM)

JCGM 100:2008 “Guide to the Expression of Uncertainty in Measurement” (GUM)

ASHRAE 150 “Thermal Storage Performance Test Procedure”

www.nist.gov