Garbage In = Garbage Out (GIGO)

Understanding the Effects of Uncertainty

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I didn’t have any accurate numbers so I just made up this one.

Studies have shown that accurate numbers aren’t any more useful than the ones you make up.

How many studies showed that?

Eighty-seven.
“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.
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*
Accuracy and Precision

Inaccurate & Precise

Inaccurate & Imprecise

Accurate & Imprecise

Accurate & Precise
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?
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)

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

**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)

\[ \eta = \frac{\text{Energy}_{\text{out}}}{\text{Energy}_{\text{in}}} \times 100 \]

\[ \eta = \frac{\text{BTU}_{\text{Steam}} - \text{BTU}_{\text{Feedwater}}}{\text{BTU}_{\text{Fuel}}} \times 100 \]

\[ \eta = \frac{(PPH_{\text{Steam}} \times h_{g,\text{steam}}) - (PPH_{\text{Feedwater}} \times h_{f,\text{feedwater}})}{\text{kcfh} \times \text{HHV}} \]
# Power Plant Example

## Characteristics

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

Efficiency = 81.4%
## Power Plant Example

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Random</th>
<th>θ</th>
<th>Systematic Contribution</th>
<th>Random Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.310</td>
<td>1.027</td>
<td>0.263682</td>
<td>0.101359</td>
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<tr>
<td>0.25</td>
<td>0.500</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.18</td>
<td>-1.100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.25</td>
<td>-0.750</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.18</td>
<td>1.300</td>
<td>0.217</td>
<td>0.001526</td>
<td>0.07958</td>
</tr>
<tr>
<td>2.00</td>
<td>0.092</td>
<td>-0.787</td>
<td>2.477476</td>
<td>0.005242</td>
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<td>0.000</td>
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<td>0</td>
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<tr>
<td>0.20</td>
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<td>0</td>
</tr>
<tr>
<td>2.00</td>
<td>2.600</td>
<td>-0.182</td>
<td>0.132496</td>
<td>0.223918</td>
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<td>0.50</td>
<td>0.200</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.13</td>
<td>0.030</td>
<td>0</td>
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<td>0.000187</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2.49499</td>
<td>0.258406</td>
</tr>
</tbody>
</table>

**Combined**

2.508336 $U_R$  
Expanded $+/-$ 5.02% $U_{R,95}$

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**RMF Engineering**

Reliability, Efficiency, Integrity
# Power Plant Example

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<tr>
<td></td>
<td></td>
<td></td>
<td><strong>0.333261</strong></td>
<td><strong>0.258406</strong></td>
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Combined: 0.421707 \( U_R \) +/− 0.84% \( U_{R,95} \)
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<td><strong>0.305902</strong></td>
<td><strong>0.258406</strong></td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>0.400437</strong></td>
<td><strong>$U_R$</strong></td>
<td><strong>Expanded</strong></td>
<td>+/- <strong>0.80%</strong> <strong>$U_{R,95}$</strong></td>
</tr>
</tbody>
</table>

The expanded uncertainty $U_{R,95}$ is calculated as $0.258406$.
99.7% of the data are within 3 standard deviations of the mean.

95% within 2 standard deviations.

68% within 1 standard deviation.
Calculating Uncertainty

**POWER**
- Fundamental: \( P_{corr} = (P_{meas} + \sum_{i=1}^{7} \Delta_i) \prod_{j=1}^{5} \alpha_j \)
- Specific: \( P_{corr} = (P_{meas} + \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4) \alpha_1 \alpha_2 \alpha_3 \)

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

\[ \frac{U_{HR_{corr}}}{HR_{corr}} = \left( \frac{U_{Q_{meas}}}{HR_{corr}} \right)^2 \left( \frac{\partial HR_{corr}}{\partial Q_{meas}} \right)^2 + \frac{U_{P_{meas}}}{HR_{corr}} \left( \frac{\partial HR_{corr}}{\partial P_{meas}} \right)^2 \]

\[ + \frac{U_{m_{therm}}}{HR_{corr}} \left( \frac{\partial HR_{corr}}{\partial m_{therm}} \right)^2 + \frac{U_{p_{f}}}{HR_{corr}} \left( \frac{\partial HR_{corr}}{\partial p_{f}} \right)^2 \]

\[ + \frac{U_{T_{inl}}}{HR_{corr}} \left( \frac{\partial HR_{corr}}{\partial T_{inl}} \right)^2 + \frac{U_{P_{amb}}}{HR_{corr}} \left( \frac{\partial HR_{corr}}{\partial P_{amb}} \right)^2 \]
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
Conclusion

• Be aware of Measurement Uncertainty.

• Identify where you could be exposed to uncertainty.

• Know how and when to control it.
References:
ASME PTC 4 “Fired Steam Generators”
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