Temperature Measurement Accuracy with RTDs
Session 1: Terminology and Error Sources

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What We'll Cover

Session 1: Terminology and Error Sources

- Terminology
- RTD accuracy
- Error sources
  - Installation
  - Instrumentation
  - Calibration

What We'll Cover

Session 2: Significance and Management of Errors

- Significance of errors
- Managing errors
  - Rules of thumb
  - Sensor selection
  - Installation recommendations

What We'll Cover

Session 3: Calculating Measurement Accuracy

- Sensor selection
  - Interchangeability
  - Performance
  - Calibration
- Transmitter or control system matching
- Calculating measurement system accuracy

Importance of Accuracy

- Consistent product quality
- Control energy costs
- Efficient production
- Third party validation

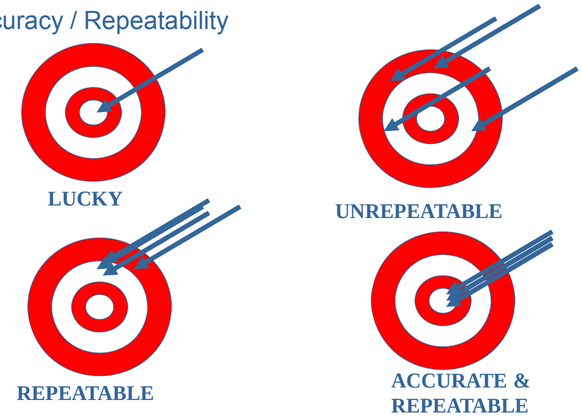
An accurate and repeatable temperature measurement is important to maintain product quality and efficient use of energy dollars.

Terminology

Accuracy	Insulation resistance
Repeatability	Hysteresis
Stability	Time response
Error	Self heating
Uncertainty	Terminology
Interchangeability	

Terminology

Accuracy / Repeatability



Hitting the bull's-eye consistently over a long time period represents excellent accuracy, repeatability, and stability.

Terminology

Error

- The difference between the measured value and the true value of temperature.

Uncertainty

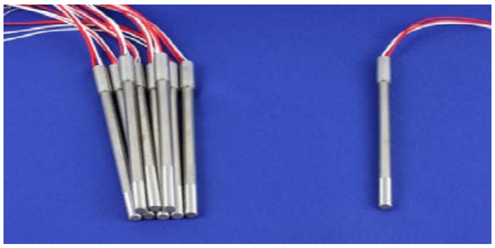
- The tolerance of the difference between a measured and/or calculated value and the true value. This includes calibration and application tolerances.

Every measurement has an error and the magnitude of that error is the uncertainty.

Terminology

Interchangeability

- Interchangeability refers to the “closeness of agreement” between an actual R vs. T relationship and a predefined R vs. T relationship.

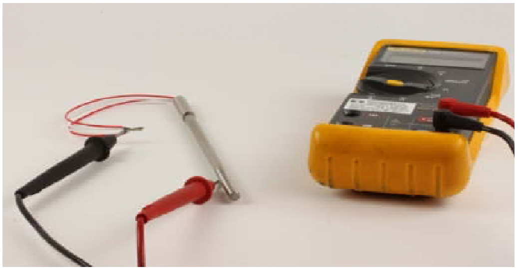


ASTM E1137 and IEC 60751 are the two most commonly used standards that define a nominal R vs. T relationship. All sensors are manufactured with 0°C as the starting point. Variations in sensors result in the tolerance increasing as the temperature diverges from 0°C.

Terminology

Insulation resistance

- Electrical resistance between the sensing circuit and the metallic sheath of a PRT



An important electrical check that should be performed as part of any calibration.

Terminology

Time response

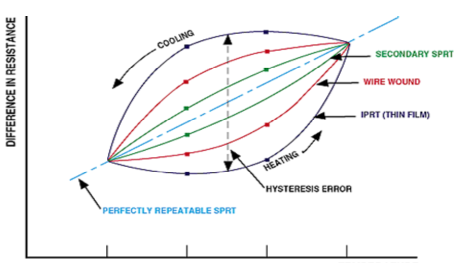
- The time required for the output of the sensor to change by 63.2% of the step change in temperature while in water moving at 3 ft/sec.

Example: A sensor is cooled to 0°C and then placed in 100°C water moving at 3 feet per second. The time required for the sensor to read 63.2°C after being plunged into the 100°C water is the time constant.

Terminology

Hysteresis

- A phenomena that results in a difference in an item's behavior when approached from a different direction



Laboratory grade sensors exhibit very little hysteresis, however industrial sensors because of their design and durability requirements have a small error attributed to hysteresis.

Terminology

Self heating

- The error produced by the heating of the PRT element due to the power applied.

The same effect that lights an incandescent bulb or a space heater that heats a room. When a current is passed through a platinum sensing element it will heat up. The current used is usually very small so the heat produced is also very small.

Error Sources

Sensor

- Interchangeability
- Insulation Resistance
- Stability
- Repeatability
- Thermal EMF
- Hysteresis
- Self Heating

Installation

- Time Response
- Stem Conduction
- Radiation
- Lead Wire
- RFI/EMI

Instrumentation

- Transmitter
- Controller/PLC

Calibration

I divided the error sources into 4 categories. A possible fifth category would be errors associated with the characteristics of the process such as mechanical shock and vibration. Both of which can cause the sensor to drift or shift in resistance, typically seen as an increase in resistance.

Sensor Errors

- Interchangeability
- Insulation Resistance
- Stability
- Repeatability
- Thermal EMF
- Hysteresis
- Self Heating

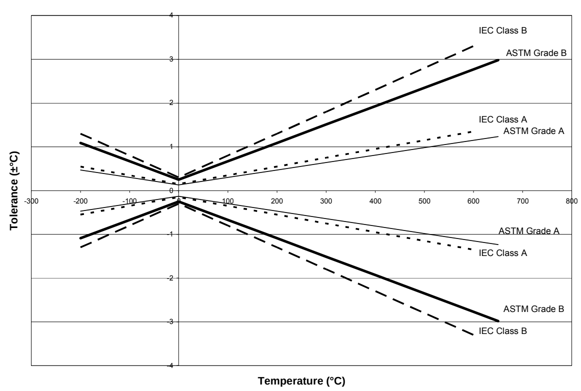
Sensor errors are only part of the total error associated with measurements made with PRTs. These are the most common.

Interchangeability

- Interchangeability refers to the "closeness of agreement" between an actual PRT R vs. T relationship and a predefined R vs. T relationship.
- Nominal R vs. T of ASTM and IEC standards are equivalent but tolerances are different.

The two main standards in use today are the IEC 60751 and the ASTM E1137. Both have the same nominal R vs. T values but differ in defining some performance characteristics and the tolerances associated with the grades or classes of sensors.

Interchangeability



Note that the ASTM standard has slightly tighter tolerances for the two grades of sensors. All RTDs are built with the tightest tolerance at 0°C and as the temperature diverges from 0°C the tolerance increases. The vertical line on the graph represents 0°C and the tolerance on the y axis is expressed in ± °C from nominal.

Interchangeability

Standard Tolerance Defining Equation[1]

ASTM E1137	Grade A	$\pm [\ .13 + 0.0017\ \lvert t \rvert\ ]$
ASTM E1137	Grade B	$\pm [\ .25 + 0.0042\ \lvert t \rvert\ ]$
IEC 60751[2]	Class AA[2]	$\pm [\ .1 + 0.0017\ \lvert t \rvert\ ]$
IEC 60751	Class A	$\pm [\ .15 + 0.002\ \lvert t \rvert\ ]$
IEC 60751	Class B	$\pm [\ .3 + 0.005\ \lvert t \rvert\ ]$
IEC 60751[2]	Class C[2]	$\pm [\ .6 + 0.01\ \lvert t \rvert\ ]$

Note 1: $\lvert t \rvert$ = absolute value of temperature of interest in °C

Note 2: These tolerance classes are included in a pending change to the IEC 60751 standard.

These equations can be used to calculate the interchangeability at any temperature. Note that the temperature t is an absolute value in °C. The resultant is the interchangeability in ± °C.

Interchangeability

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Examples:

Temp.	Grade A	Class A	Grade B	Class B
0°C	±.13°C	.15	.25	.30
100°C	±.30°C	.35	.67	.80
200°C	±.47°C	.55	1.09	1.30
300°C	±.64°C	.75	1.51	1.80
400°C	±.81°C	.95	1.93	2.30

Calculating the interchangeability at 200°C shows the difference between the grades or classes of sensors. Grade A or Class A has the tighter tolerances.

Interchangeability

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Temp. °C	Resistance of Element Ohms	Interchangeability ± °C	
		0.05%	0.10%
-150	38.77	.40	.75
-100	59.68	.31	.50
-50	80.03	.22	.28
0	100.00	.14	.28
50	119.66	.22	.28
100	139.02	.31	.50
150	158.08	.40	.75

Temp. °C	Resistance of Element Ohms	Interchangeability ± °C	
		0.05%	0.10%
200	176.85	.50	1.00
250	195.33	.63	1.25
300	213.52	.75	1.50
350	231.42	.87	1.75
400	249.03	1.00	2.00
450	266.34	1.13	2.25
500	283.36	1.25	2.50

A lookup table may be more convenient and the intermediate values can be interpolated between listed points. Also note that this manufacturer has chosen to hold tighter tolerances than either of the two standards. Rather than ± 0.06% and ± 0.12% from the standards, these values are ± 0.05% and ± 0.10%.

Insulation Resistance

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- Error is caused by inability to measure actual resistance of element
- Current leaks into or out of the circuit, or between the element leads
- Changes in IR result in changes in PRT resistance reading

Moisture or contamination inside the sensor sheath can cause low IR. This will cause the sensor to read a lower than actual temperature.

Insulation Resistance

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Standard	Temp (°C)	Min. IR (MΩ)	Estimated Error (100 ohm PRT(°C))
ASTM E1137	25	100	.0003
ASTM E1137	300	10	.013
ASTM E1137	650	2	.17
IEC 60751	25	100	.0003
IEC 60751	100 to 300	10	.013
IEC 60751	301 to 500	2	.12
IEC 60751	501 to 850	0.5	1.0

IR decreases as the temperature increases. The standards differ in how the error is estimated. Low IR at low temperatures causes a similar error to that at higher temperatures.

Long Term Stability (Drift)

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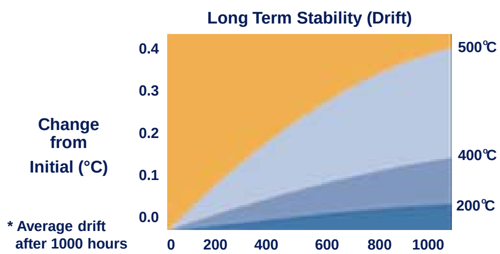
Definition

- The state of being resistant to change or deterioration over time.



Temperatures from 0°C to 400°C result in small drift rates. Increasing to 500°C dramatically increases the drift rate. After 1000 hours the rates fall to about half of what they are in the first 1000 hours.

Repeatability

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- Ability to maintain R vs. T under the same conditions after experiencing thermal cycling throughout a specified temperature range.
- Typically expressed as % change in ice point resistance after 10 consecutive cycles over the sensor temperature range.

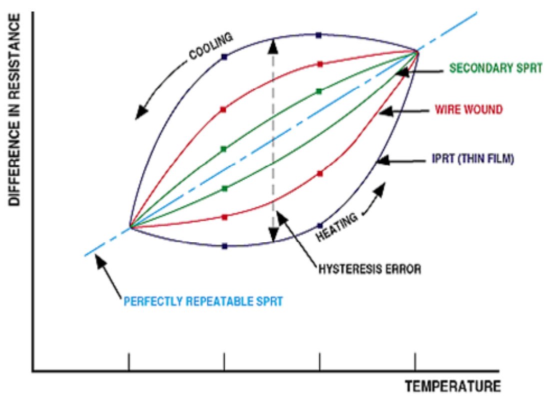
Smaller temperature ranges result in better repeatability. A typical value for an RTD with a -200°C to 500°C temperature range is less than ± 0.04% change in ice point resistance.

Hysteresis

- Ability to maintain R vs. T relationship when approaching temperatures from different directions and magnitudes.
- Worst case is at mid-point between maximum and minimum rated temperatures.

Typically a small error in a properly designed RTD. Ruggedizing the sensing element for industrial environments typically increases the hysteresis error.

Hysteresis



This graph shows the difference between the laboratory RTDs and the industrial grade sensors. Lab grade sensors (SPRT) show very little or no error as shown by the straight blue line.

Self Heating

- Error produced by the heating of the PRT element due to the power applied.
- Self heating errors for 100Ω PRTs are generally < 0.01°C when placed in process with good heat transfer.
- Larger errors can occur under the following conditions:
  - High resistance sensors, 500 or 1000 Ω
  - Low heat transfer conditions, still air or low pressure gases

Much like an incandescent light bulb that glows and heats up when a current passes through, an RTD element will also heat up. Usually the current is very small so the error is small. Magnitude if affected the heat transfer between the sensor and process fluid.

Thermal EMF

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- Thermal EMF errors are produced by the EMF adding to or subtracting from the applied sensing voltage, primarily in DC systems.
- Example:
  100 Ω PRT at 200°C with an EMF of 50μV.
  - Using 1 mA current the error would be 0.12°C
  - This example assumes DC, no EMF compensation

Junctions of dissimilar metals inside the sensor can cause an EMF (electro motive force or voltage) which can cause an error. Magnitude of the error is dependent on the current used and the temperature.

Installation Errors

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- Time Response
- Stem Conduction
- Lead Wire
- Radiation
- Convection

These can be some of the largest errors and great care should be taken to insure that the proper sensor and installation configuration are used to minimize errors.

Time Response

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- Errors are produced during temperature transients because the PRT cannot respond to changes fast enough.
- No error at steady state.
- Some processes require fast response to changes, others prefer slow response.
- Transmitters can influence time response.

A process that is changing rapidly needs a sensor that can keep up to the changes. Errors of several degrees can easily occur if the sensor responds too slowly. In some cases it may be necessary to slow down the sensor response so it doesn't respond to transients such as a freezer door being opened to remove or place product. Sensor design can be changed or a transmitter can be added to the circuit and set to delay measurements.

Time Response

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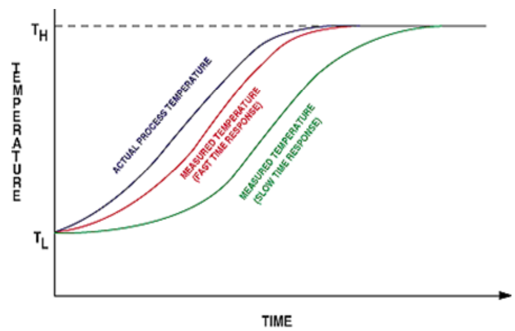

This graph shows the error when a sensor that has a slow time response is used in a rapidly changing process (T_L to T_H)

Stem Conduction

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- Error that results from the PRT sheath conducting heat into or out of the process.
- Users must be aware that significant errors can be produced in use that don't show up in lab testing/calibration.

This may be the most common error with PRTs and can be very large. Much like a car radiator the external parts of the sensor conduct heat into and out of the process. If the sensor is not immersed far enough into the process the sensing element will detect the extra heat.

Immersion Depth

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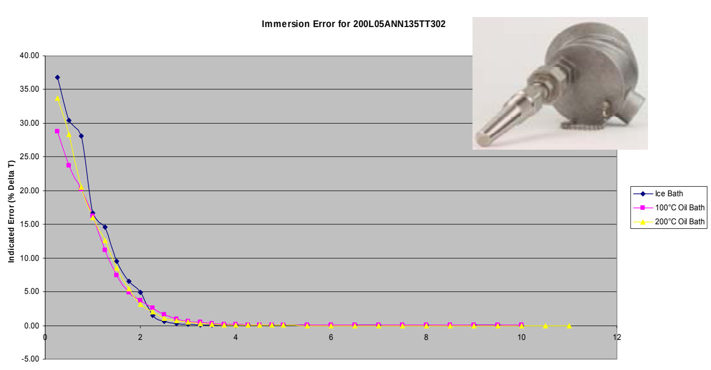


A thermowell/RTD assembly was immersed in a bath to determine the stem conduction at various depths. At 4.5 inches most of the error has disappeared.

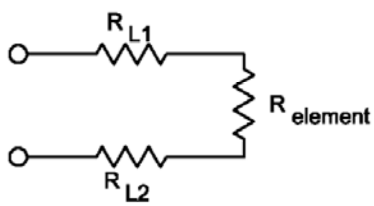
As you can see the error is mostly independent of the bath temperature used. As an example a thermowell with 2.5" immersion gives us an error of about 0.45°C.

Lead Wire Error

- 2 wire connection adds lead resistance in series with PRT element.
- 3 wire connection relies on all 3 leads having equal resistance.
- 4 wire connection eliminates error

Lead wires used to connect the sensor to a process control instrument can cause a measurement error. Two and three wire circuits have the largest errors and the 4 wire will nearly eliminate the error.

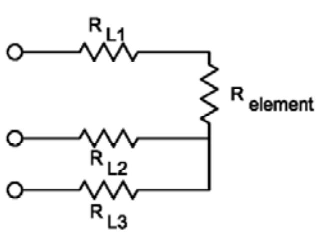
Lead Wire Error



$$R_{measured} = R_{L1} + R_{element} + R_{L2}$$

Two wire circuits simply add the lead resistance to the sensing element resulting in very large errors.

Lead Wire Error

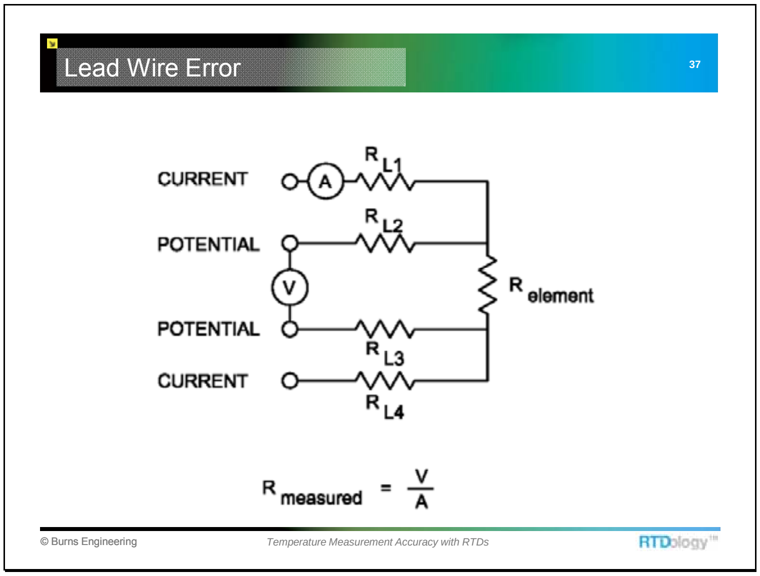


$$R_{measured} = R_{L1} + R_{element} + R_{L2} - [R_{L2} + R_{L3}]$$

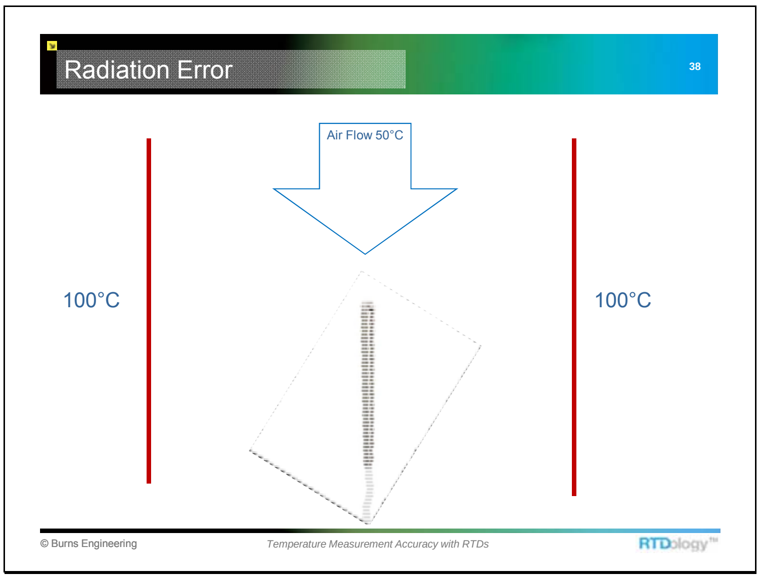
$$= R_{L1} + R_{element} - R_{L3}$$

$$= R_{element} \quad (\text{if } R_{L1} = R_{L3})$$

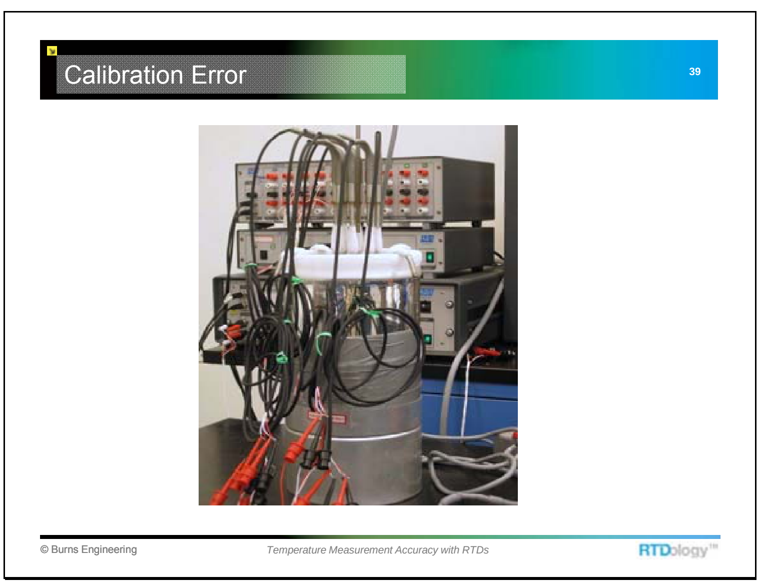
A three wire circuit will add no error if each of the three legs have the same resistance. Unfortunately in the real world there is a difference and that causes an error.



The current potential method or 4 wire circuit is the most accurate and has little or no error associated with it.



Radiated heat from a source colder or hotter than the fluid being measured can have an affect on the measured temperature. Add a shield to the sensor to block the radiation.



Every sensor has a resistance check performed to determine if it is within tolerance. That process has an error associated with it that needs to be added to the sensor error.

Calibration Error

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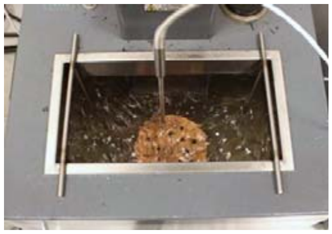
Calibration uncertainty

- Temperature distribution and stability of the calibration media
- Calibration standard
- Resistance measurement device
- Interpolation errors
- Sensor stability



These are the sources of error associated with the calibration. Each is very small but still need to be taken into consideration.

Significance of Errors

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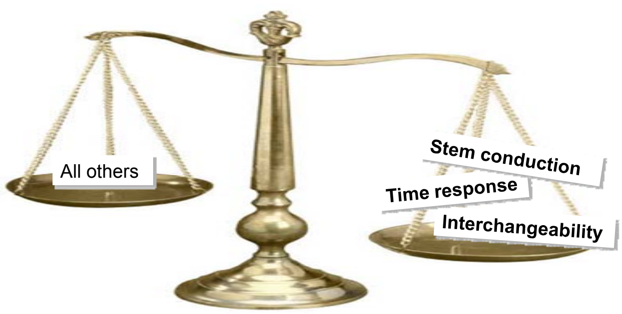

Our next session will attempt to quantify the error sources and show that the stem conduction, time response, and interchangeability are the largest and far outweigh the others.

Summary

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- There are numerous sources of error
- Installation errors can be more significant than sensor errors
- Interchangeability is about 85% of the sensor accuracy
- Nothing is certain
- Next session March 7
  - Significance of errors
  - Managing errors
    - ✓ Rules of thumb
    - ✓ Sensor selection
    - ✓ Installation recommendations

Questions?

Use the chat window to send us a question now.

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- Session II: Significance & Management of Errors
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Measuring Temperature in Small Diameter Lines

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