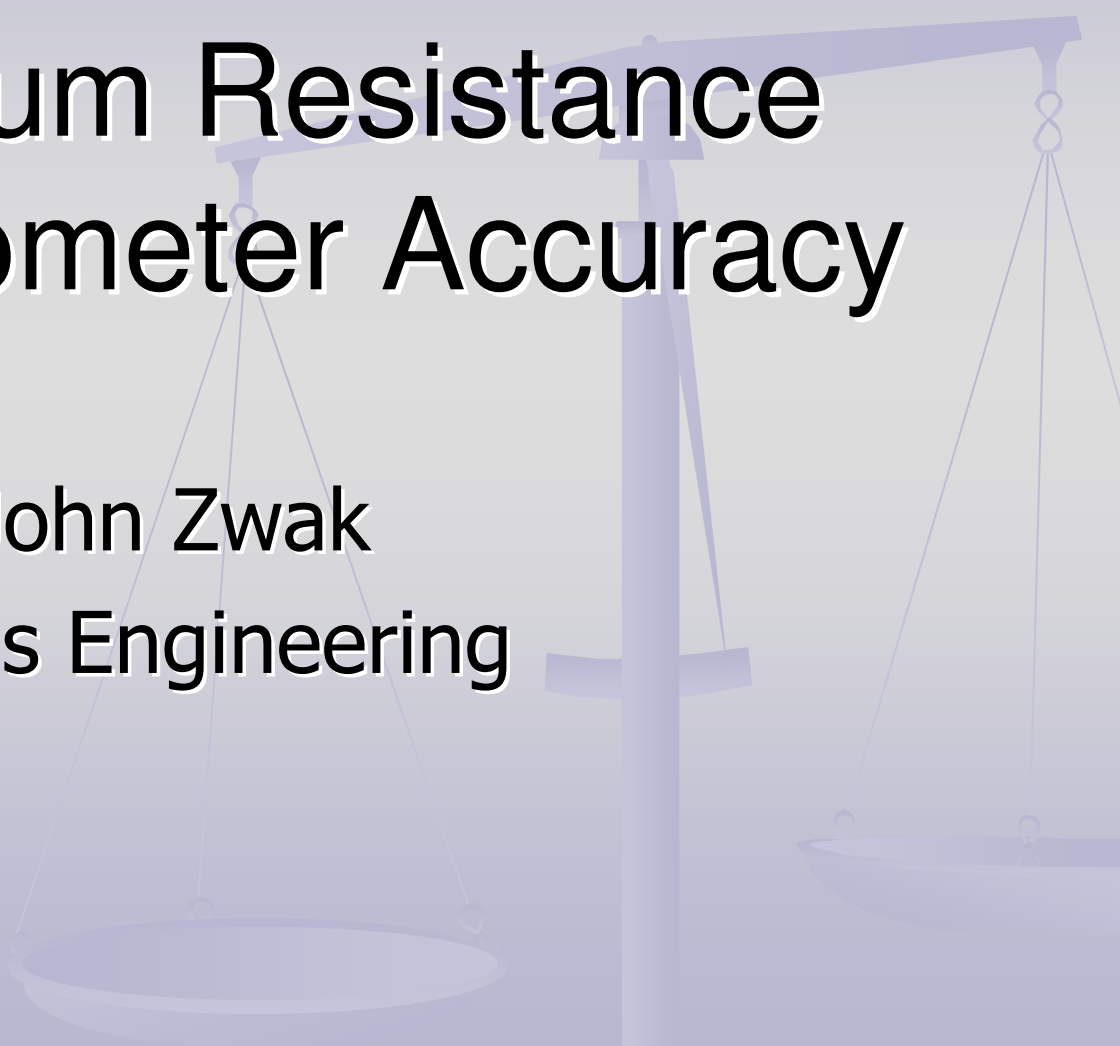


# Error Sources That Effect Platinum Resistance Thermometer Accuracy



John Zwak  
Burns Engineering



# Presentation Outline

- How a PRT works.
- Error Sources
- Combining and Estimating Errors



# How a PRT Works

- PRTs use a resistor made from platinum.
- Resistance of platinum is dependent on temperature, impurities, and deformation.

$$R_{\text{total}} = R_{\text{temperature}} + R_{\text{impurities}} + R_{\text{deformation}}$$

- For PRT, we want only resistance caused by temperature.



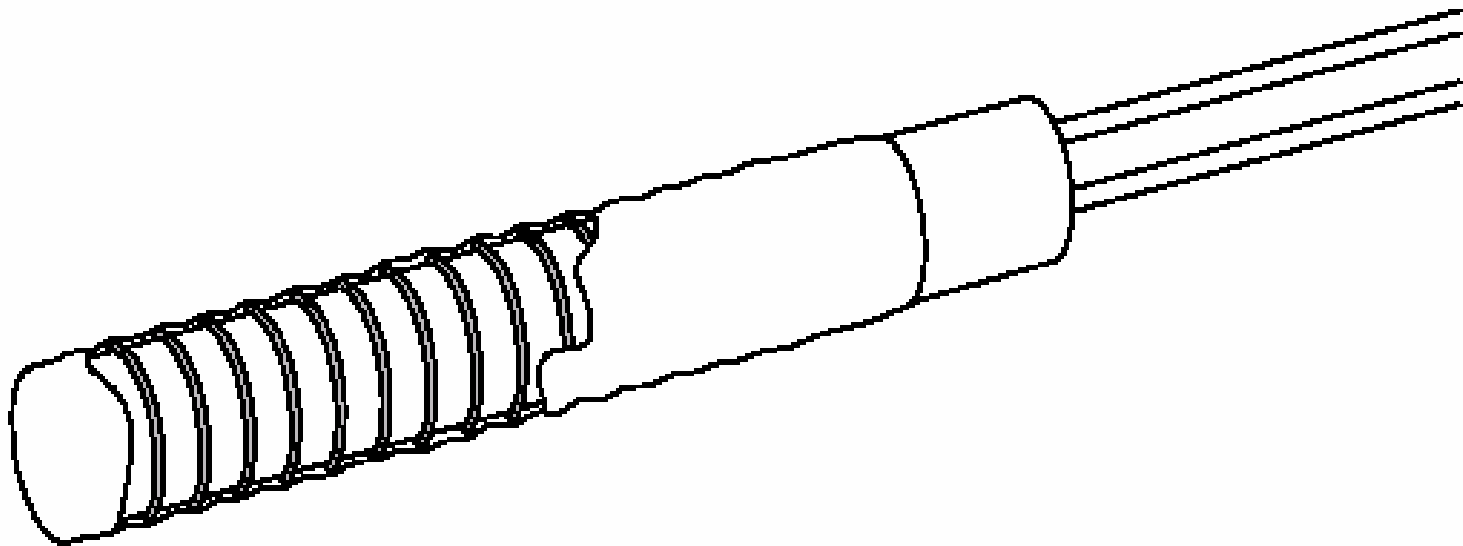
# How a PRT Works

## ■ Advantages of Platinum

- Resistance is nearly linear with temperature
- Works over very large range (-269 °C to +961 °C)
- Noble metal, immune to contamination
- Available in very high purities
- In part, PRTs define temperature on the ITS-90 scale

# Anatomy of a PRT

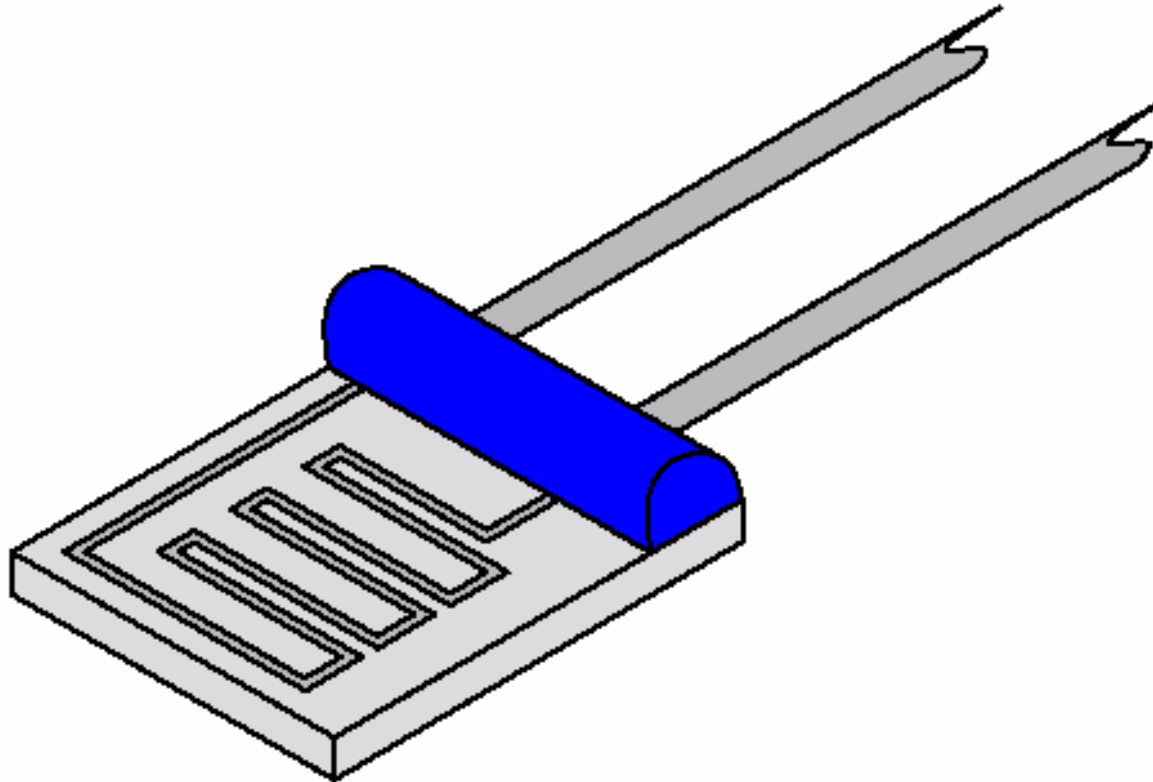
- Sensing element is a resistor made from Platinum and ceramics.



Externally wound element

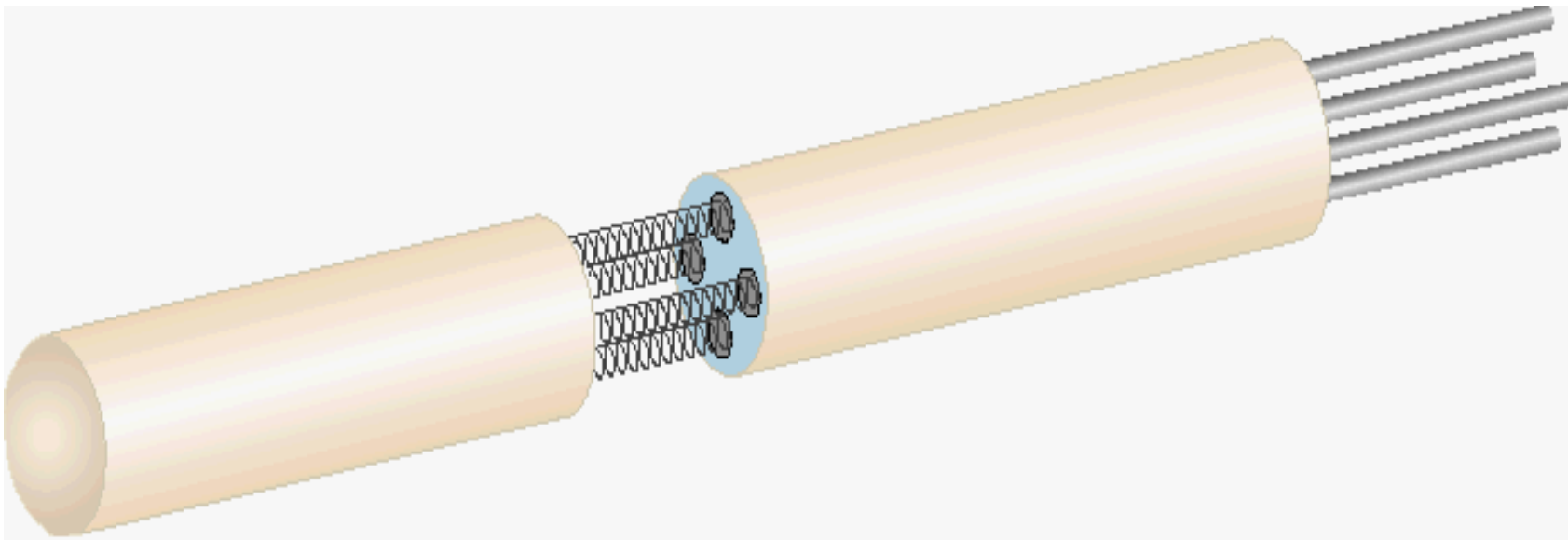
# Anatomy of a PRT

- Thin Film Element

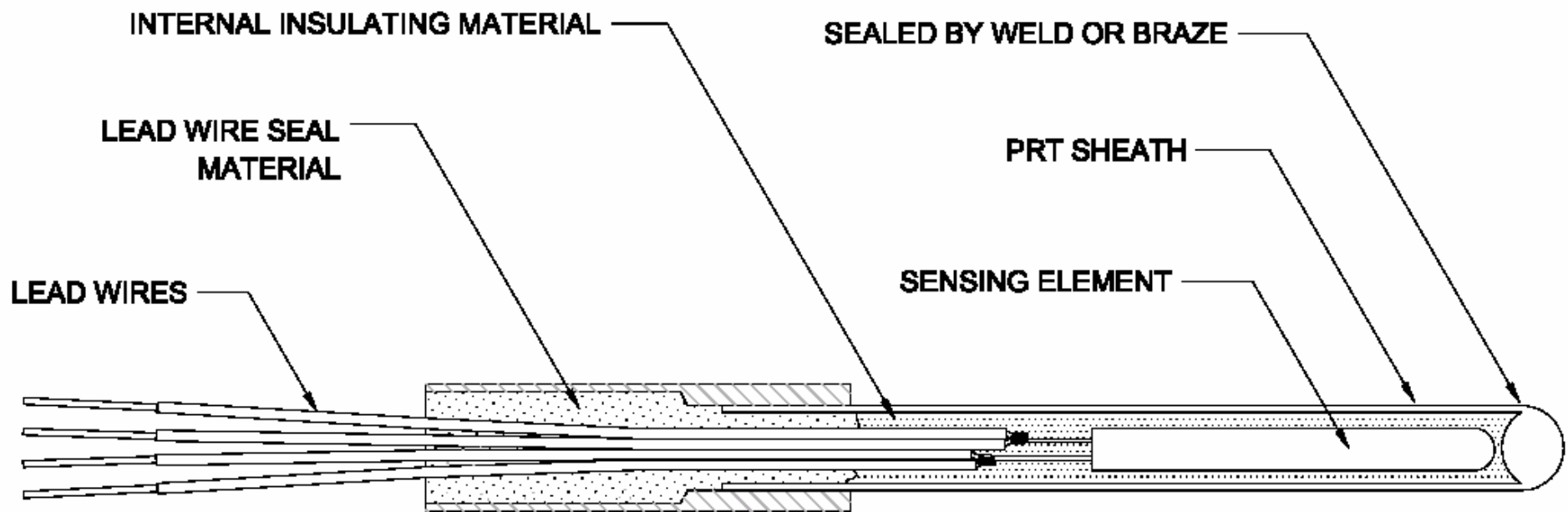


# Anatomy of a PRT

- Coil Element



# Anatomy of a PRT





# PRT Standards

- Common industrial PRT standards:
  - ASTM E1137
  - IEC 60751
  - DIN 43760
- All agree on same R vs T
  - 385 Alpha ( $.00385\Omega/\Omega/^{\circ}\text{C}$  TCR)
- No standards for secondary standard PRT



# Error Recognition – PRT Specific

- Error – The difference between the temperature determined by the PRT and the true value of temperature.
- Many individual sources contribute to total error.
- Magnitude of error from each source can vary greatly.
- Sources come from the inherent properties of PRTs, design compromises, installation compromises.



# Common Error Sources

- Common errors sources:

Interchangeability

Stability

Hysteresis

Calibration/Interpolation

Self Heating

Thermal EMF

Insulation Resistance

Repeatability

Stem Conduction

Lead Wire

Time Response

Others



# Interchangeability



# 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, IEC, DIN standards are equivalent but tolerances are different.

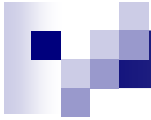


# Interchangeability

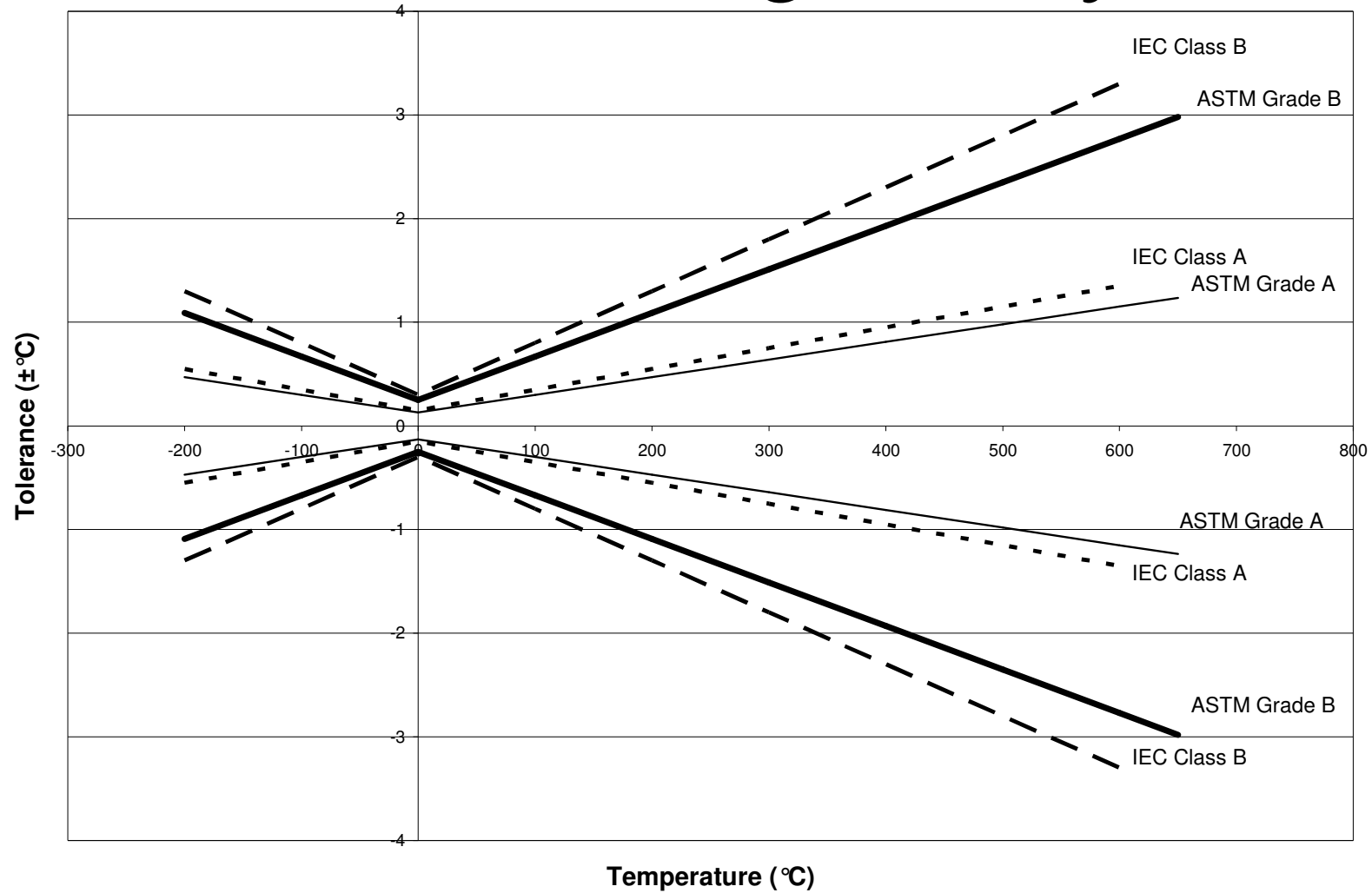
<b>Standard</b>	<b>Tolerance</b>	<b>Defining Equation<sup>1</sup></b>
ASTM E1137	Grade A	$\pm [ .13 + 0.0017   t   ]$
ASTM E1137	Grade B	$\pm [ .25 + 0.0042   t   ]$
IEC 60751 <sup>2</sup>	Class AA	$\pm [ .1 + 0.0017   t   ]$
IEC 60751	Class A	$\pm [ .15 + 0.002   t   ]$
IEC 60751	Class B	$\pm [ .3 + 0.005   t   ]$
IEC 60751 <sup>2</sup>	Class C	$\pm [ .6 + 0.01   t   ]$

Note 1:  $| t |$  = the value of temperature in °C without regard to sign.

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



# Interchangeability





# Interchangeability

Examples:

<b>Temp.</b>	<b>Grade A</b>	<b>Class A</b>	<b>Grade B</b>	<b>Class B</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



# Interchangeability

- Design and Manufacturing considerations are primary cause.
- Ways to reduce interchangeability error:
  - Select a PRT with tight interchangeability
    - Generally limited to small temp ranges
  - Calibrate sensor and match transmitter to actual PRT R vs T.
    - With good cal, transmitter becomes limiting item

# Interchangeability

- Matched transmitter example:
  - PRT in a process at 121 °C using a transmitter with .1 °C accuracy.

	<b>Grade B</b>	<b>Grade A</b>	<b>Calibrated</b>
	<b>Sensor</b>	<b>Sensor</b>	<b>Sensor</b>
Sensor Tol at 121C	±.76 °C	.34	.05
Transmitter Accuracy	±.1 °C	.1	.1
<b>Combined System (RSS)</b>	<b>± .77 °C</b>	<b>.35</b>	<b>.11</b>



# Insulation Resistance



# Insulation Resistance

- 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.
- ASTM and IEC standards provide limits on IR.
- Typically error is estimated as two resistors in parallel.



# Insulation Resistance

<b>Standard</b>	<b>Temp (°C)</b>	<b>Min. IR (MΩ)</b>	<b>Estimated Error (100 ohm PRT(°C))</b>
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	.5	1.0



# Insulation Resistance

- Causes of low IR
  - Moisture within PRT
    - Leaky seal
    - Trapped during original manufacture
  - Non-moisture contaminant
  - Physical damage to PRT
    - Bent sheath
    - Dented sheath
    - Damaged seal area



# Insulation Resistance

- Ways to minimize
  - Choose PRT that is designed properly
    - Adequate insulation/spacing
    - Seal can handle thermal/mechanical environment
  - Early detection of problems
    - Measure IR often



# Stability



# Stability

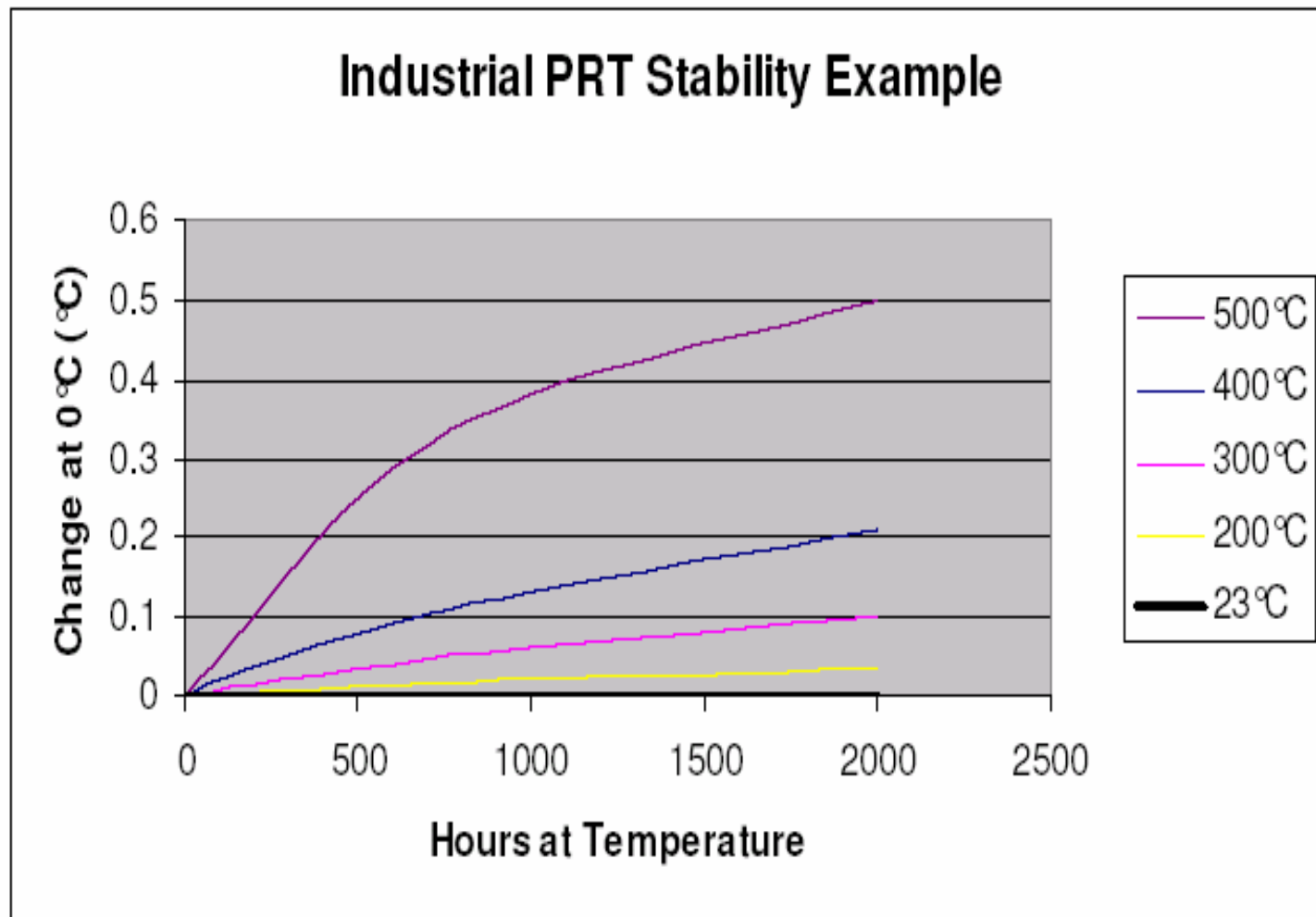
- Ability to maintain R vs T over time as a result of thermal exposure.
- ASTM test requires 672 hours of soak at max rated temperature, must meet resistance tolerance.
- IEC test requires 250 hours of soak at max rated temperature, allows shift of  $.15/.30^{\circ}\text{C}$  at  $0^{\circ}\text{C}$ .
- Both lack real world conditions (8760 hours/year).



# Stability

- Ideally want to know rate per 1000 hours at max rated temp as well as 3 to 4 other temps to allow interpolation.

# Stability





# Stability

- Can conservatively but more realistically estimate annual changes.
- Example: PRT used continuously for 1 year (~9000 hours) at 350 °C.
  - ASTM = 1.69 °C
  - IEC = 5.26 °C
  - Data from graph = .9 °C      (.1 °C/1000 hours)



# Stability

- Primary cause is contamination of platinum due to design and manufacture.
- Ways to minimize stability error
  - Select a PRT with a low specified stability at the maximum temperature of use
  - Never expose a PRT to temperatures above maximum rated temperature.
  - Avoid unnecessary exposure to elevated temp to minimize cumulative affect.
  - Periodically calibrate and match transmitter to new R vs T relationship.



# Repeatability



# Repeatability

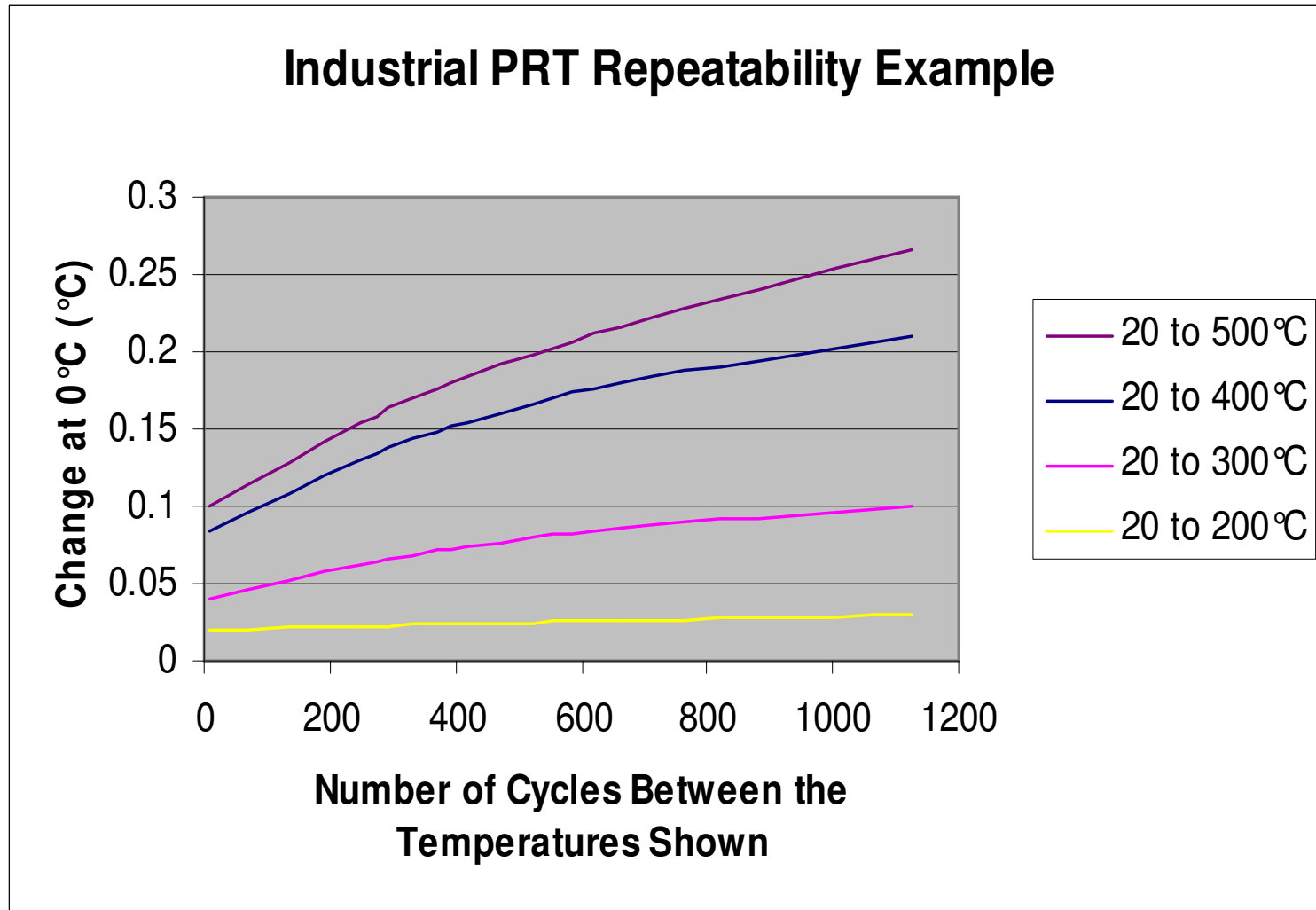
- Ability to maintain R vs T under the same conditions after experiencing thermal cycling throughout a specified temperature range.
- ASTM does not have a requirement.
- IEC allows .15/.30 °C change per 10 thermal cycles between upper and lower temperatures.
- Both lack performance info in real world conditions.



# Repeatability

- Ideally want to know change over various ranges and various numbers of cycles.
  - Ranges from small up to maximum rated temperature range
  - Cycles up to 1000

# Repeatability





# Repeatability

- Can conservatively and realistically estimate annual changes.
- Example: PRT cycled from room temp to 350 °C for 1 hour, 3 times per day for a year.
  - $3 \times 365 = 1095$  cycles/year
  - From graph, estimate is .16 °C
  - Estimate does not include stability error for 1095 hours at 350 °C.



# Repeatability

- Primary cause of this error is strain in the fine diameter pt wire or film. Controlled almost exclusively by the design.
- Ways to minimize repeatability error.
  - Select a PRT with a low specified repeatability over the range of use.
  - Periodically calibrate and match the transmitter to new R vs T relationship, however, not all repeatability is removed in doing this.



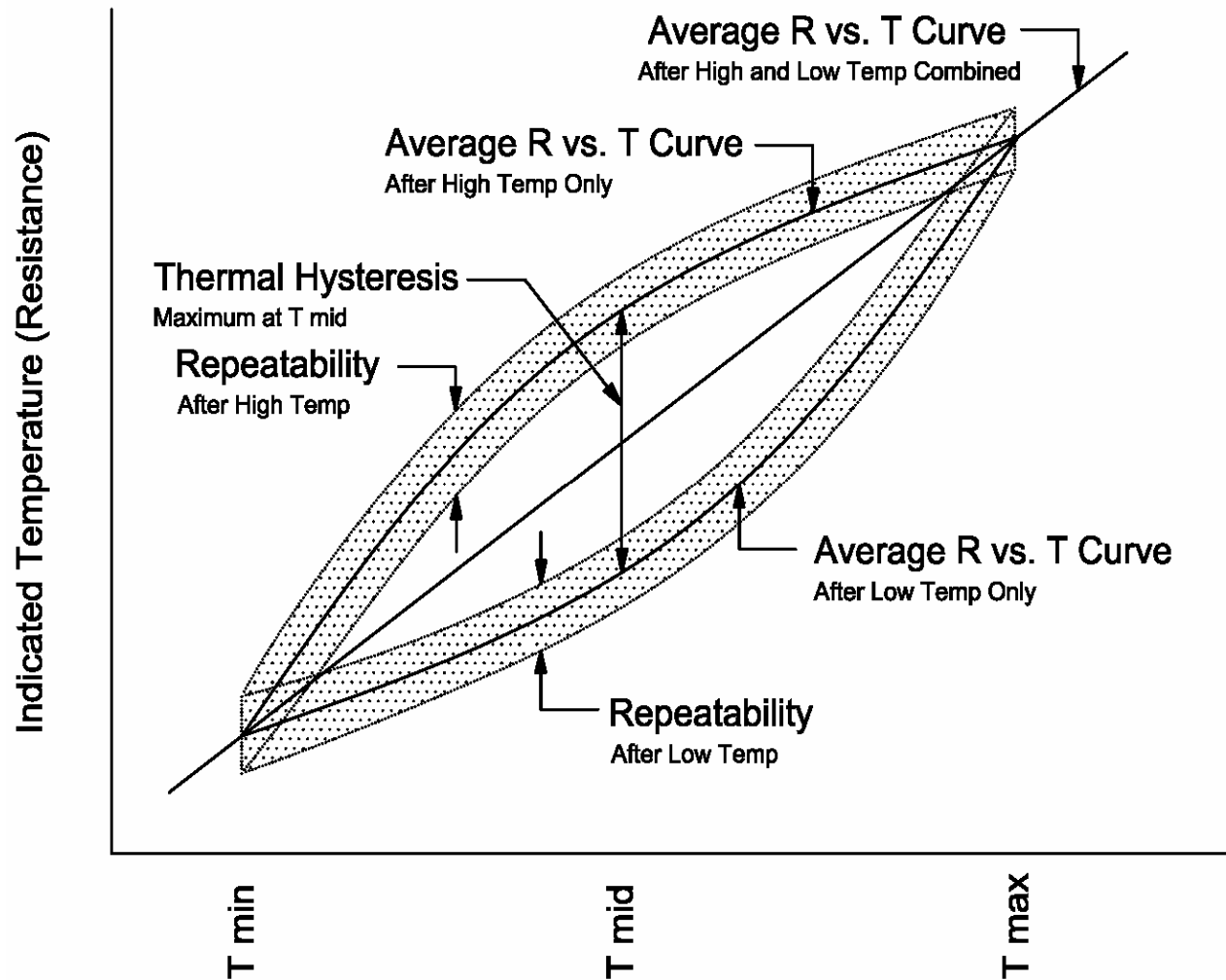
# Hysteresis



# 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.
- ASTM does not have a requirement.
- IEC allows a max difference equal to the resistance tolerance at the test temperature.
- Not uncommon for manufacturers to spec as a flat error in °C.

# Hysteresis





# Hysteresis

- Ideally want to know the error as a percentage of the temperature span.
- Assume the max error at the mid point, zero error at the max and min temperatures, and interpolate linearly between.
- Hysteresis can be negligible or as much as .1% of the span.
- Example: A sensor with a specified hysteresis of .05% of span that operates from 0 to 400 °C would have a .2 °C hysteresis error at 200 °C.



# Hysteresis

- Primary cause is strain in platinum due to differential thermal expansion and contraction of surrounding materials.
- Element design is primary driver.
- Ways to minimize hysteresis error.
  - Select a PRT with a low specified hysteresis.
  - Do not expose PRT to temperature ranges wider than necessary.



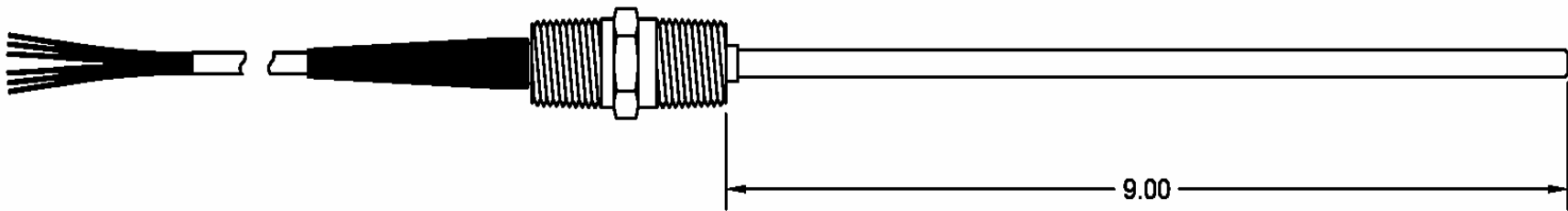
# Stem Conduction



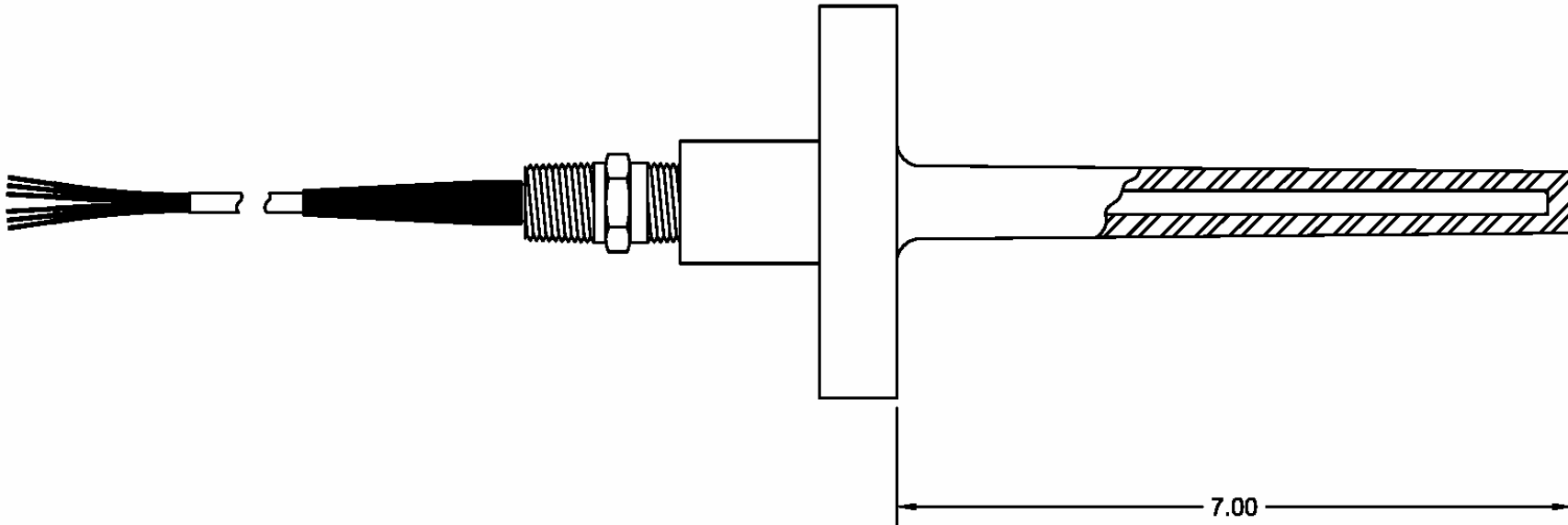
# Stem Conduction

- Error that results from the PRT sheath conducting heat into or out of the process.
- ASTM specifies  $.13/.25^{\circ}\text{C}$  error with 2" immersed in ice bath.
- IEC requires the “minimum immersion depth” to be that where a  $.1^{\circ}\text{C}$  error is produced in  $85^{\circ}\text{C}$  water.
- Users must be aware that significant errors can be produced in use that don't show up in lab testing/calibration.

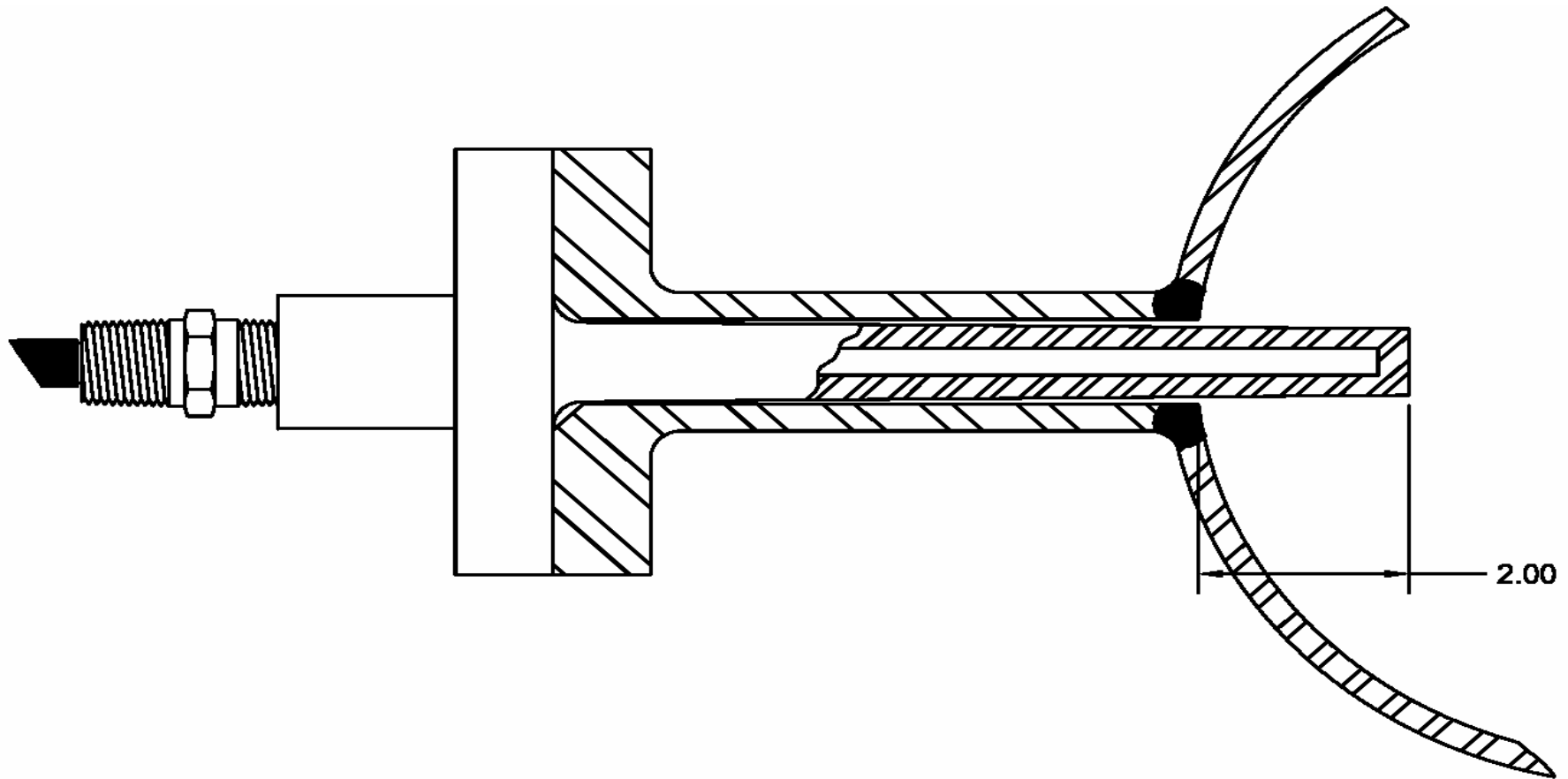
# Stem Conduction



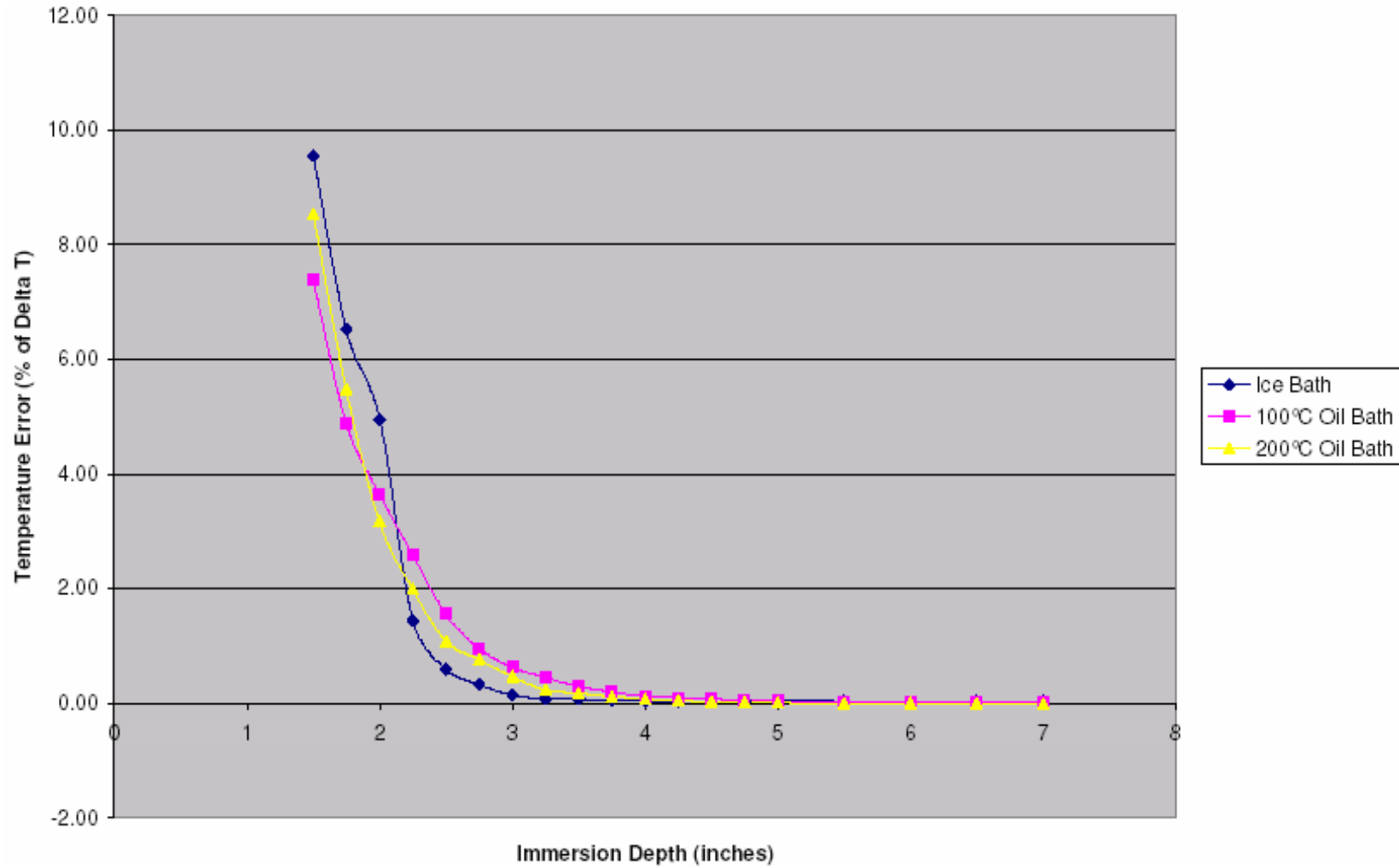
# Stem Conduction



# Stem Conduction



# Stem Conduction





# Stem Conduction

- Difficult to analyze, can be very sensitive to depth.
- Ideal immersion is at least 10x the sheath diameter plus the element length into the process.
  - 3.5" for .25 sheath
  - 1.5" for .125 sheath.
- Heat transfer conditions heavily influence this.
- Error proportional to  $\Delta T$ .



# Stem Conduction

- Cause of error is inadequate immersion into the process.
- Ways to minimize stem conduction error.
  - Follow mfg guidelines for immersion.
  - Use special tip sensitive designs.
  - Insulate portion of sensor external to process.
  - Consult manufacturer for appropriate sensor.



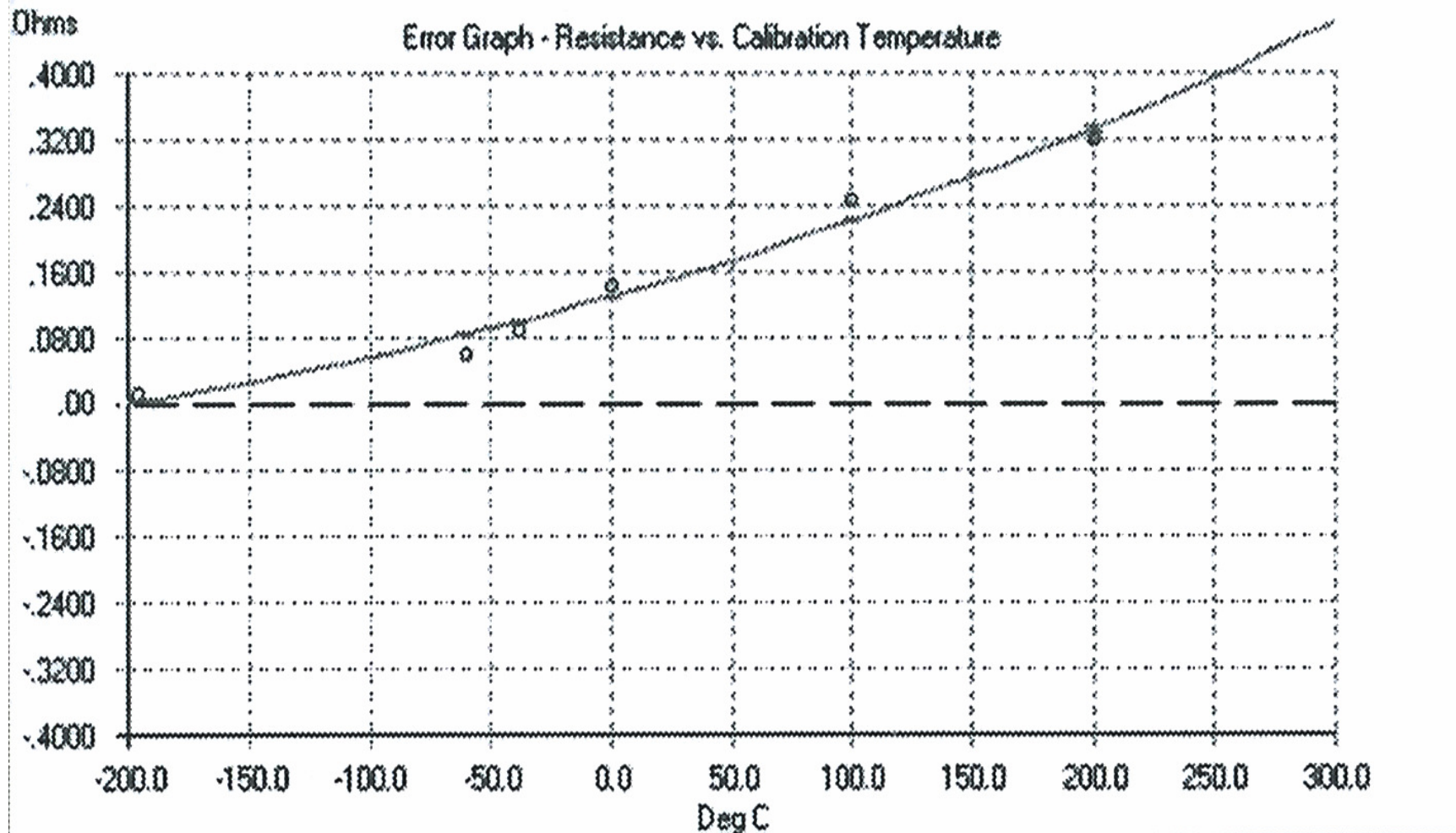
# Calibration and Interpolation



# Calibration and Interpolation

- Errors that occur due to calibration uncertainty at the cal points, or between cal point due to propagation of uncertainty or curve fit errors.
- ASTM and IEC do not address this beyond the resistance tolerance limits.
- Only a factor when using custom R vs T relationships.

# Calibration and Interpolation





# Calibration and Interpolation

- Calibration uncertainties range from a few mK on up.
  - Caused by cal method and UUT performance.
  - To minimize, select a cal lab with low uncertainties and a PRT with low repeatability/hysteresis.
- Curve fit errors are generally  $<.07^{\circ}\text{C}$  below  $0^{\circ}\text{C}$ , and  $<.03^{\circ}\text{C}$  above  $0^{\circ}\text{C}$ .
  - Caused by propagation of cal uncertainties and non-ideal equations.
  - To minimize, select a cal lab with low uncertainties and a PRT with low repeatability/hysteresis.



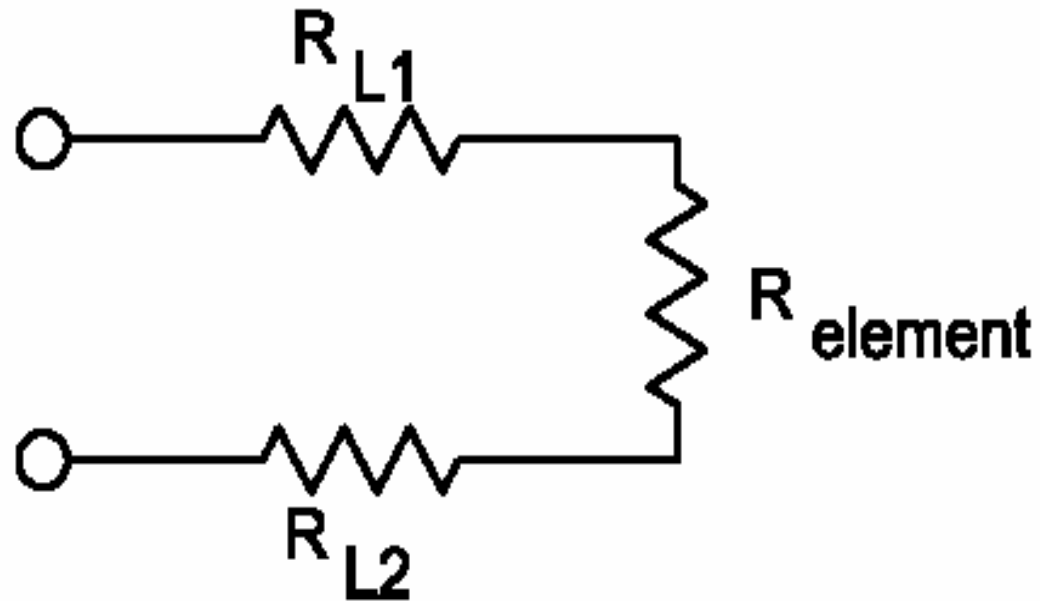
# Lead Wire Error



# Lead Wire Error

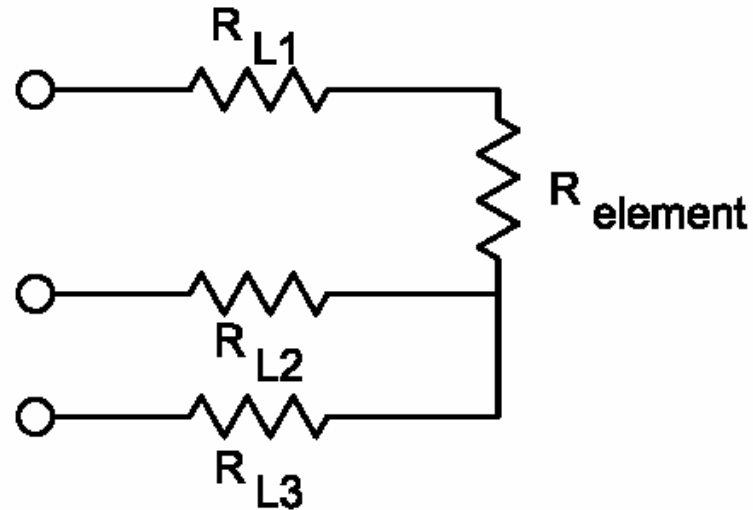
- Errors that occur because a 4 wire measurement is not used.
  - 2 wire connection adds lead resistance in series with PRT element.
  - 3 wire connection relies on all 3 leads having equal resistance.
- ASTM and IEC do not specify errors from lead wires.

# Lead Wire Error



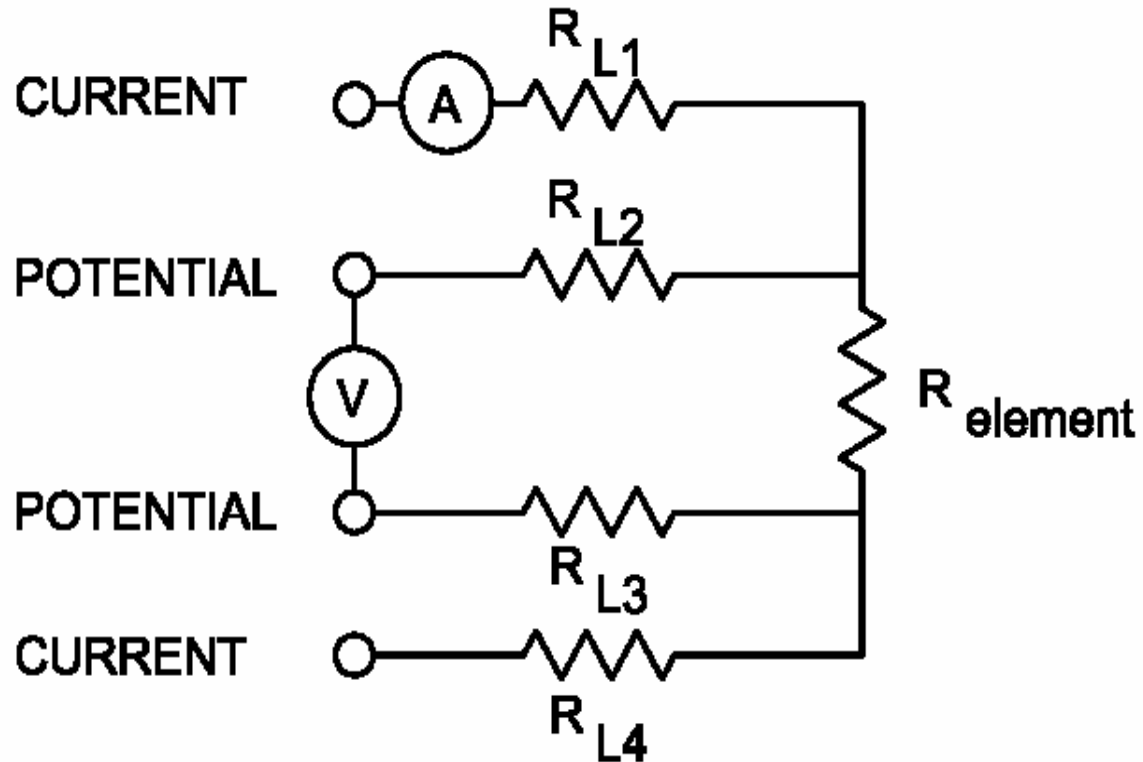
$$R_{\text{measured}} = R_{L1} + R_{\text{element}} + R_{L2}$$

# Lead Wire Error



$$\begin{aligned}R_{\text{measured}} &= R_{L1} + R_{\text{element}} + R_{L2} - [R_{L2} + R_{L3}] \\ &= R_{L1} + R_{\text{element}} - R_{L3} \\ &= R_{\text{element}} \quad (\text{if } R_{L1} = R_{L3})\end{aligned}$$

# Lead Wire Error



$$R_{\text{measured}} = \frac{V}{A}$$



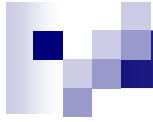
# Lead Wire Error

- For 3-wire sensors, error is directly related to variation in lead resistance.
  - Every .04 ohm variation results in  $\sim .1$  °C error.
- Examples – assume 10% mismatch in resistance worst case.
  - 22 AWG copper, nominal resistance  $.016\Omega/\text{foot}$ 
    - $.004$  °C/foot error, typical 10' cable =  $.04$  °C error
  - 30 AWG copper, nominal resistance  $.104 \Omega/\text{foot}$ 
    - $.026$  °C/foot error, typical 10' cable =  $.26$  °C error



# Lead Wire Error

- Lead wire errors are caused by resistance being added or subtracted from element resistance.
- Ways to minimize
  - Use a 4 wire measurement
  - Use a wire size appropriate for cable length
  - Match transmitter to PRT using specific wire connections



# Self Heating



# Self Heating

- Error produced by the heating of the PRT element due to the power applied.
- ASTM requires error be no more than 1 °C when 33 mW are applied in 25 °C water.
- IEC requires error be no more than .05/.10 °C at 25 °C in water or air when maximum current is used.



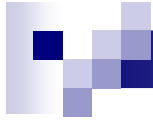
# Self Heating

- Most transmitters use 1mA or less so the power to a 100  $\Omega$  PRT is small, .02 to .39 mW.
- Self heating errors for 100 $\Omega$  PRTs are generally  $<.01$   $^{\circ}\text{C}$  when placed in process with good heat transfer.
- Larger errors can occur under the following conditions:
  - High resistance sensors, 500 or 1000 $\Omega$
  - Low heat transfer conditions, still air or low pressure gases



# Self Heating

- Self heating errors are caused by the inability of the element to dissipate the heat generated by the power supplied.
- To minimize self heating errors
  - Select a PRT with good self heating characteristics
  - Use a low measuring current, 1mA max
  - Use a 100  $\Omega$  PRT
  - Locate PRT where there is good heat transfer (moving product)

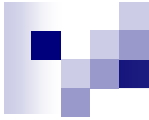


# Time Response

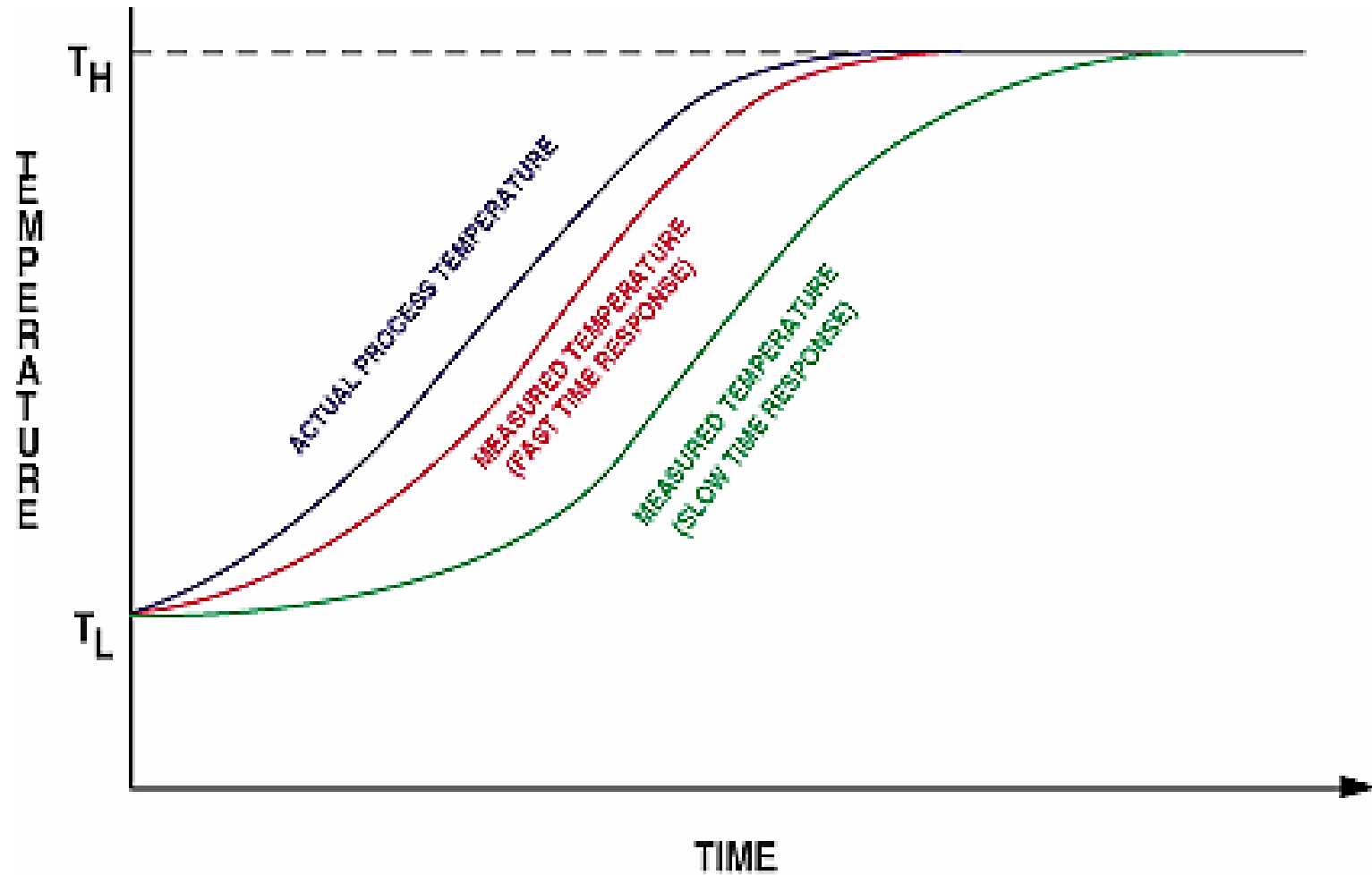


# Time Response

- Errors are produced during temperature transients because the PRT cannot respond to changes fast enough.
- No error at steady state.
- ASTM and IEC do not specify temperature errors, rather they discuss time.
- Some processes require fast response to changes, others prefer slow response.
- Transmitters can influence time response.



# Time Response





# Time Response

- Time response error is caused by the inability of the PRT to track the process temperature.
- To minimize response time error.
  - Choose a PRT with a faster response.
  - Smaller diameter
  - Special designs
  - Use transmitters properly



# Thermal EMF



# Thermal EMF

- Thermal EMF errors are produced by the EMF adding to or subtracting from the applied sensing voltage, primarily in DC systems.
- ASTM requires PRT to meet resistance tolerance at max rated temperature when 1mA is applied.
- IEC requires difference in PRT measurements at max rated temp using max current to be less than the resistance tolerance.
- Both standards are adequate for higher sensing currents but lack info about small currents where affect would be larger.



# Thermal EMF

- Example:

- 100  $\Omega$  PRT at 200 °C with an EMF of 50 $\mu$ V.

- Using 1mA current the error would be .12 °C

- Using .1mA current the error would be 1.2 °C.

This example assumes DC, no EMF compensation



# Thermal EMF

- Thermal EMF error is caused by a combination of:
  - Internal and external connecting wire composition, inhomogeneity, connections, and temperature gradients within the PRT.
  - Circuitry used to measure the resistance.
- To minimize thermal EMF error:
  - Use a PRT with a low specified EMF
  - Use appropriate circuitry, AC
  - Minimize unnecessary temperature gradients



# Other Sources



# Other Sources

- Other sources can produce errors but are difficult to analyze without installation unique information.
  - Vibration
  - Mechanical Shock
  - Thermal Shock
  - Pressure
  - Thermal Radiation
  - Nuclear Radiation



# Combining Errors

- Determine each error component individually at the temperature of interest.
- Sum the errors using RSS.
- Example:
  - A Class A sensor is cycled 3 times per day from room temp to 350 °C for 1 hour. What is estimated annual change at 0 °C and at 350 °C? Assume sensor performance is similar to the performance described in the earlier examples.
    - Total annual cycles: 1095
    - Total hours at 350 °C: 1095



# Combining Errors

- Individual errors at 0 °C:
  - Interchangeability:  $\pm .15$  °C
  - Insulation Resistance:  $\pm .0003$  °C
  - Stability:  $\pm .11$  °C
  - Repeatability:  $\pm .16$  °C
  - Hysteresis:  $\pm 0$  °C (end point)
  - Stem Conduction:  $\pm 0$  °C (adequate immersion)
  - Cal and Interpolation:  $\pm 0$  °C (using nominal R vs T)
  - Lead Wire Resistance:  $\pm .04$  °C (3 wire, 10' of 22AWG)
  - Self Heating:  $\pm .01$  °C
  - Time Response:  $\pm 0$  °C (steady state)
  - Thermal EMF:  $\pm 0$  °C (AC circuit)

**RSS Total =  $\pm .25$  °C**

# Combining Errors

- Same example except calibrated sensor
- Individual errors at 0°C:
  - Interchangeability:  $\pm 0^\circ\text{C}$
  - Insulation Resistance:  $\pm .0003^\circ\text{C}$
  - Stability:  $\pm .11^\circ\text{C}$
  - Repeatability:  $\pm .16^\circ\text{C}$
  - Hysteresis:  $\pm 0^\circ\text{C}$  (end point)
  - Stem Conduction:  $\pm 0^\circ\text{C}$  (adequate immersion)
  - Cal and Interpolation:  $\pm .05^\circ\text{C}$
  - Lead Wire Resistance:  $\pm .04^\circ\text{C}$  (3 wire, 10' of 22AWG)
  - Self Heating:  $\pm .01^\circ\text{C}$
  - Time Response:  $\pm 0^\circ\text{C}$  (steady state)
  - Thermal EMF:  $\pm 0^\circ\text{C}$  (AC circuit)

**RSS Total =  $\pm .20^\circ\text{C}$**




# Estimating Errors at Other Temperatures

- More difficult process, only a rough estimate.
- Some errors are dependent on the R0 change.
  - Stability
  - Repeatability
- For these errors, multiply the change at 0°C by the nominal ratio of the  $R_t/R_0$  for the temperature of interest. For our example, at 350°C  $R_t/R_0 = 2.3$ 
  - Stability,  $\pm 0.11$  °C at 0°C,  $\sim \pm 0.25$  °C at 350°C
  - Repeatability,  $\pm 0.16$  °C at 0°C,  $\sim \pm 0.37$  °R at 350°C



# Estimating Errors at Other Temperatures

- Some errors are independent of R0 change and vary greatly between temperatures.
  - Interchangeability
  - Insulation Resistance
  - Hysteresis
- For these errors, handle as follows for our example:
  - Interchangeability, from Standard,  $\pm 0.85^\circ\text{C}$  at  $350^\circ\text{C}$
  - Insulation Resistance, estimate  $\pm 0.12^\circ\text{C}$  at  $350^\circ\text{C}$
  - Hysteresis,  $\pm 0^\circ\text{C}$  because  $350^\circ\text{C}$  is an end point (for non-end points, use max value at mid point temp, 0 at end point temps, linear interpolation between these temps.)



# Estimating Errors at Other Temperatures

- Some errors do not vary significantly between temperatures.
  - Calibration and Interpolation
  - Lead wire
- For these errors estimate the same value at temperature as at 0 °C, for our example.
  - Calibration and Interpolation, 0 °C if using nominal R vs T relationship,  $\pm .05$  °C if using calibrated.
  - Lead wire, .04 °C at all temperatures.



# Estimating Errors at Other Temperatures

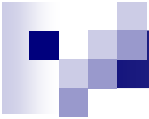
- Some errors are dependent on installation/use conditions.
  - Stem conduction
  - Self heating
  - Thermal EMF
- For these errors more information is required. Be aware that these are possible sources, but for our example assume the same error as used at 0°C



# Estimating Errors at Other Temperatures

- Individual errors at 350 °C:
  - Interchangeability:  $\pm .85$  °C
  - Insulation Resistance:  $\pm .12$  °C
  - Stability:  $\pm .25$  °C
  - Repeatability:  $\pm .37$  °C
  - Hysteresis:  $\pm 0$  °C (end point)
  - Stem Conduction:  $\pm 0$  °C (adequate immersion)
  - Cal and Interpolation:  $\pm 0$  °C (using nominal R vs T)
  - Lead Wire Resistance:  $\pm .04$  °C (3 wire, 10' of 22AWG)
  - Self Heating:  $\pm .01$  °C
  - Time Response:  $\pm 0$  °C (steady state)
  - Thermal EMF:  $\pm 0$  °C (AC circuit)

**RSS Total =  $\pm .97$  °C**



# Estimating Errors at Other Temperatures

- Same example except calibrated sensor
- Individual errors at 350 °C:
  - Interchangeability:  $\pm 0^{\circ}\text{C}$
  - Insulation Resistance:  $\pm .12^{\circ}\text{C}$
  - Stability:  $\pm .25^{\circ}\text{C}$
  - Repeatability:  $\pm .37^{\circ}\text{C}$
  - Hysteresis:  $\pm 0^{\circ}\text{C}$  (end point)
  - Stem Conduction:  $\pm 0^{\circ}\text{C}$  (adequate immersion)
  - Cal and Interpolation:  $\pm .05^{\circ}\text{C}$
  - Lead Wire Resistance:  $\pm .04^{\circ}\text{C}$  (3 wire, 10' of 22AWG)
  - Self Heating:  $\pm .01^{\circ}\text{C}$
  - Time Response:  $\pm 0^{\circ}\text{C}$  (steady state)
  - Thermal EMF:  $\pm 0^{\circ}\text{C}$  (AC circuit)

**RSS Total =  $\pm .47^{\circ}\text{C}$**

NCSLI - June 5, 2008



# Conclusions

- Many sources contribute to the total error, some are PRT driven, some are use driven.
- ASTM E1137 and IEC 60751 standards provide some performance information, but it is not comprehensive or particularly stringent.
- Knowing PRT accuracy is not enough.
- Specific details must be known about the application for an accuracy estimate to be made.



Thank You