Burns Engineering, Inc.
Presents

RTD Accuracy III

Calculating Measurement Accuracy

If you are experiencing audio problems or are not able to listen through your PC,
please call the teleconference number below (US/Canada):

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Access code 664 732 738

Bill Bergquist

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Special Guest

- Patrick Callaghan, Design Engineer
  - Joined Burns recently
  - BS Chemical Engineering
  - MS Mechanical Engineering
  - Emphasis in Biomedical Engineering

What We've Covered

- Session 1: RTD Accuracy
  - Terminology
  - Error sources
    - Sensor
    - Installation
    - Instrumentation
    - Calibration
- See the presentation notes at: http://www.burnsengineering.com/rtdology/

What We've Covered

- Session 2
  - Significance of errors
  - Managing errors
    - Rules of thumb
    - Sensor selection
    - Installation recommendations
  - See the presentation notes at: http://www.burnsengineering.com/rtdology/

Today's Session

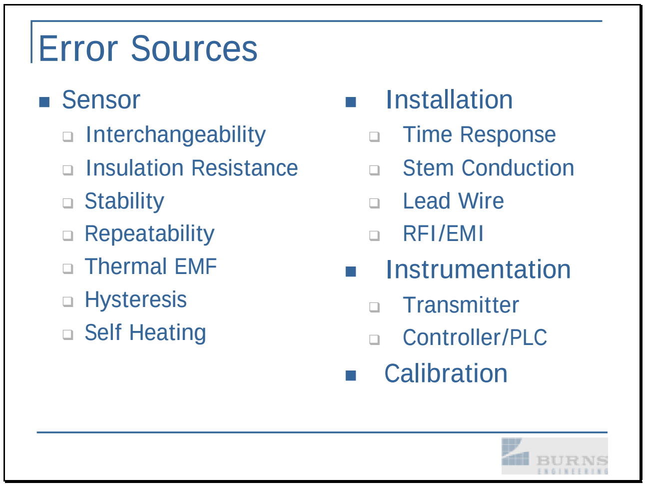
- Session 3
  - Calculating measurement system accuracy
    - Sensor selection
    - Performance
    - Calibration

The purpose of session 3 is to demonstrate how the numerous error sources contribute to the accuracy calculation. Also we want to show how the installation errors are a large contributor to the measurement error.

Importance of Temperature Accuracy

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

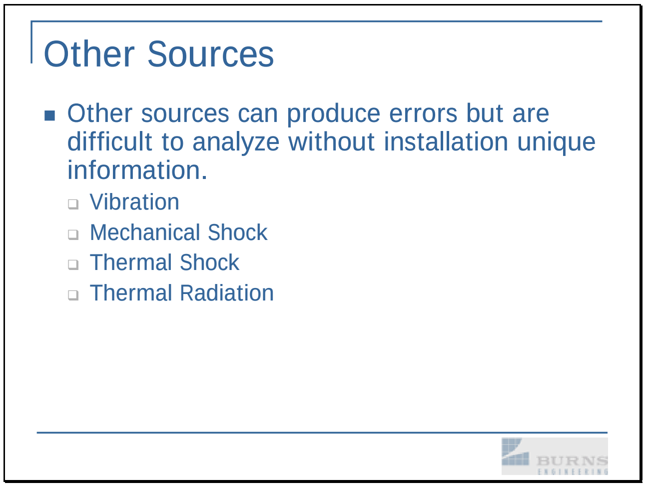
An accurate and repeatable temperature measurement is important to maintain product quality and efficient use of energy $'s.



Error Sources

- Sensor
  - Interchangeability
  - Insulation Resistance
  - Stability
  - Repeatability
  - Thermal EMF
  - Hysteresis
  - Self Heating
- Installation
  - Time Response
  - Stem Conduction
  - Lead Wire
  - RFI/EMI
- Instrumentation
  - Transmitter
  - Controller/PLC
- Calibration

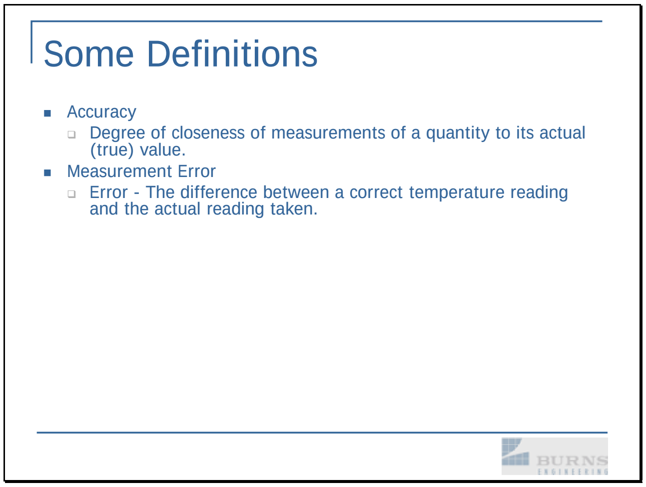
I divided the error sources into 4 categories. A possible fifth category would be errors associated with the characteristics of the process such as mechanical shock and vibration. Both of which can cause the sensor to drift or shift in resistance typically seen as an increase in resistance.



Other Sources

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

These are a few other potential error sources. Application specific information is necessary to estimate the size of error.



Some Definitions

- Accuracy
  - Degree of closeness of measurements of a quantity to its actual (true) value.
- Measurement Error
  - Error - The difference between a correct temperature reading and the actual reading taken.

Some Definitions

- Uncertainty*
  - In metrology, measurement uncertainty is a central concept quantifying the dispersion one may reasonably attribute to a measurement result. Such an uncertainty can also be referred to as a measurement error.
  - The most commonly used procedure for calculating measurement uncertainty is described in the Guide to the Expression of Uncertainty in Measurement (often referred to as "the GUM") published by ISO. A derived work is for example the National Institute for Standards and Technology (NIST) publication NIST Technical Note 1297 "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results" and the Eurachem/Citac publication "Uncertainty in measurements" (available at the Eurachem homepage). The uncertainty of the result of a measurement generally consists of several components. The components are regarded as random variables, and may be grouped into two categories according to the method used to estimate their numerical values:
  - Type A, those evaluated by statistical methods
  - Type B, those evaluated by other means, e.g., by assigning a probability distribution
  - By propagating the variances of the components through a function relating the components to the measurement result, the combined measurement uncertainty is given as the square root of the resulting variance. The simplest form is the standard deviation of a repeated observation.

*From Wikipedia

If you search Wikipedia for uncertainty you will get links to more information about this broad topic. There are multi-day classes devoted to this often confusing topic. We do not have the time to go through it in detail, only to say that it exists and needs to be taken into consideration when calculating measurement accuracy.

Game Plan

- We picked a typical application to use as an example for making our measurement accuracy calculations.

The example is from a previous session on application and selection.

The Application

- A 4” pipe with a water-like fluid moving at 100 ft/sec, 65°C (150°F)
- 2.5” immersion
- 100 ohm PRT per ASTM E1137 Grade B
- Transmitter with matching capability
- Ambient 20°C
- Control to ± 0.5°C

Our sample application is water flowing in a pipe and is a good demonstration of the many error sources present.

Error	Value in °C	Source
Interchangeability		
Insulation Resistance		
Stability		
Repeatability		
Thermal EMF		
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		

A table was constructed to track the error, value, and source of the information.

Error	Value in °C	Source
Transmitter		
Controller/PLC		
RFI/EMI		
Calibration		
Vibration		
Mechanical Shock		
Thermal Shock		
Thermal Radiation		

Page 2 of errors. There are others but these are the most common.

Method

- Root-Sum-Square, or sum of the squares
  - Identify the errors, square them, add them together and then take the square root

$$\text{Error} = \sqrt{A^2 + B^2 + C^2 + D^2}$$

RSS was chosen because it is a common method to combine the errors in a statistically meaningful manner.

Method

- Apply a coverage factor such as k=2 for 95% confidence level

Accuracy = error x 2

A coverage factor is used to boost the confidence level of the measurement accuracy estimate. k=2 is 95% confidence and k=3 is >99%. For more information see http://physics.nist.gov/cuu/Uncertainty/coverage.html

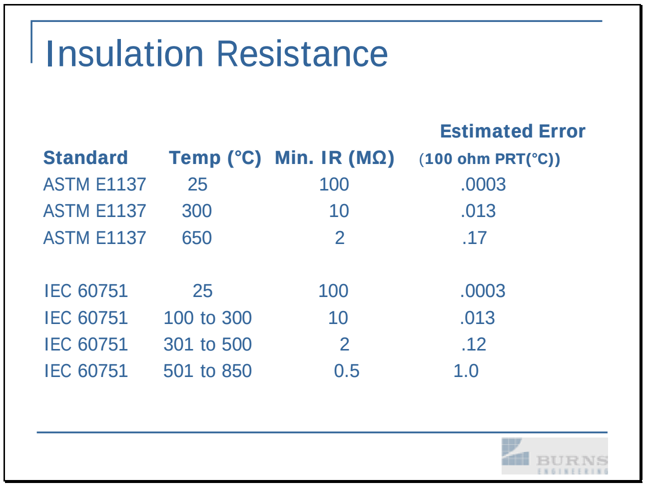
Interchangeability

- ASTM E1137 Grade B ± [.25 + 0.0042 | t |]
  - | t | for our application is 65°C
  - Solving, our interchangeability is **± 0.523°C**

One of the larger sensor errors is interchangeability. Values can be found in the ASTM E1137 or IEC 60751 standards. Manufacturer's data may also be used.

For our example we will use the ASTM standard and select the equation for the grade B. Substituting 65°C for the absolute value t and solving returns ± 0.523°C.

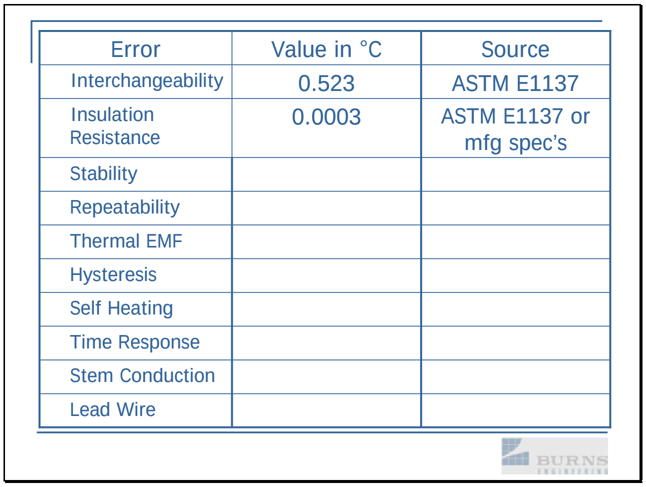
Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance		
Stability		
Repeatability		
Thermal EMF		
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		



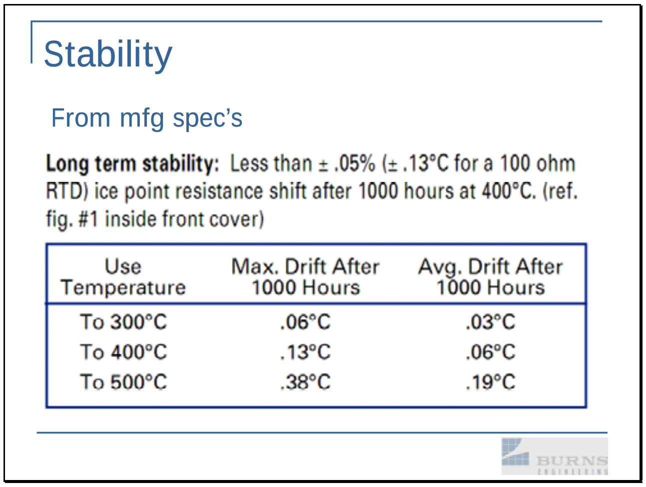
Insulation Resistance

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

For our calculation we can use the 25°C range and 100 megohms with a .0003 error. As you may recall IR decreases as the temperature increases but 65°C is close enough to 25 and the error small enough so we can use the .0003 number with some confidence. Also note that low IR at low temperatures causes a similar error to that at higher temperatures. So if your sensor has failed low during an IR test and you want to look up the effect on accuracy, use the IR number that most closely matches, regardless of the temperature.



Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability		
Repeatability		
Thermal EMF		
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		



Stability

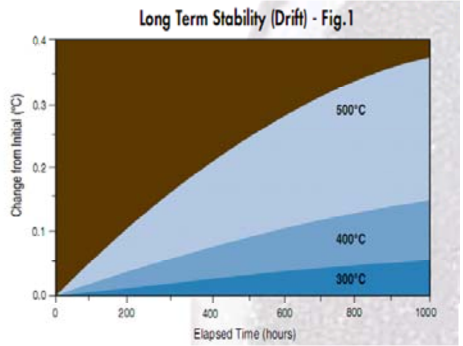
From mfg spec's

Long term stability: Less than ± .05% (± .13°C for a 100 ohm RTD) ice point resistance shift after 1000 hours at 400°C. (ref. fig. #1 inside front cover)

Use Temperature	Max. Drift After 1000 Hours	Avg. Drift After 1000 Hours
To 300°C	.06°C	.03°C
To 400°C	.13°C	.06°C
To 500°C	.38°C	.19°C

You will have to depend on the RTD manufacturers specification to determine a realistic stability error based on the RTD design and installation specifics. Many times the application does not correspond to the specifications as is the case for our example. We are running at 65°C and the nearest table value is at 300°C. Referring to the figure #1 referenced we can get a little better estimate.

Stability



Estimating from the graph we can see that a reasonable value is 0.01°C. It is a good idea to consult with the manufacturer to confirm the value.

Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability	0.01	Mfg spec's
Repeatability		
Thermal EMF		
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		

Repeatability

From mfg spec's

Repeatability: Less than ± .04% change in ice point resistance after 10 consecutive cycles between -200 and 500°C.

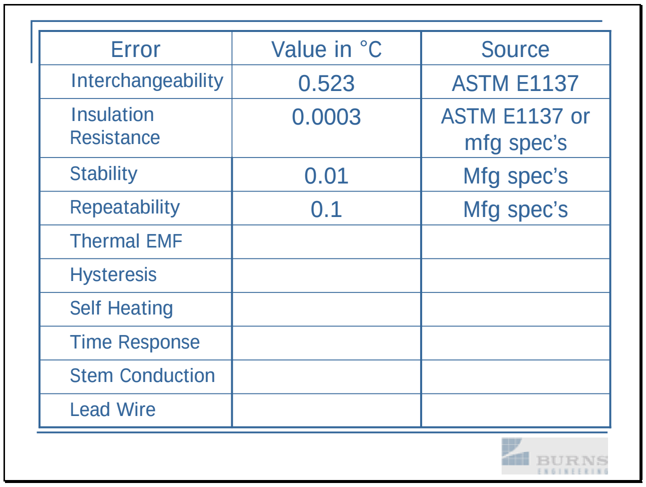
Repeatability = .04% x 100 ohms

= .04 ohms

Converting to °C

.04 ohms /.385 ohms/°C = 0.1°C

Our temperature range is much smaller but the only data we have from the mfg specification is -200 to 500C. Using this value and converting from resistance to degrees C gives us 0.1°C.



Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
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Stability	0.01	Mfg spec's
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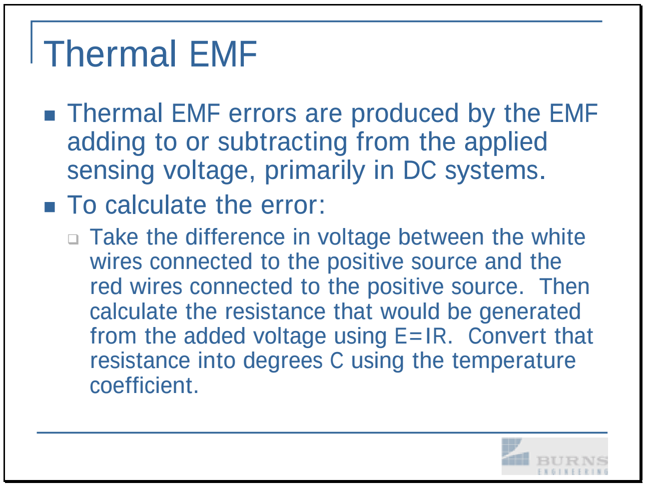
Thermal EMF		
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		

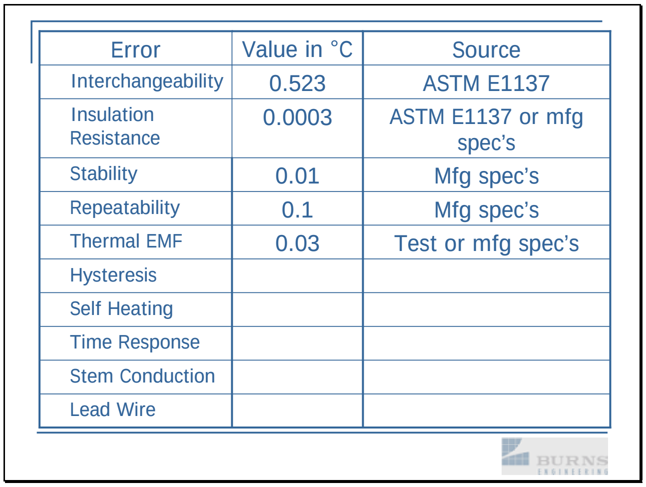


Thermal EMF

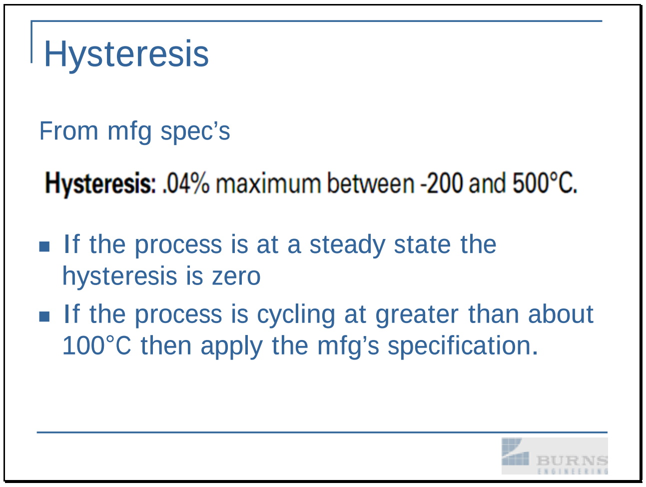
- Thermal EMF errors are produced by the EMF adding to or subtracting from the applied sensing voltage, primarily in DC systems.
- To calculate the error:
  - Take the difference in voltage between the white wires connected to the positive source and the red wires connected to the positive source. Then calculate the resistance that would be generated from the added voltage using E=IR. Convert that resistance into degrees C using the temperature coefficient.

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. For our example using mfg specifications the error is about .03°C.



Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability	0.01	Mfg spec's
Repeatability	0.1	Mfg spec's
Thermal EMF	0.03	Test or mfg spec's
Hysteresis		
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		



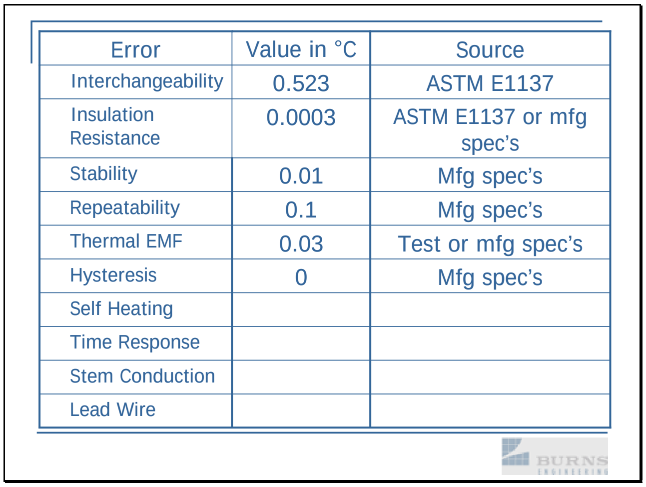
Hysteresis

From mfg spec's

Hysteresis: .04% maximum between -200 and 500°C.

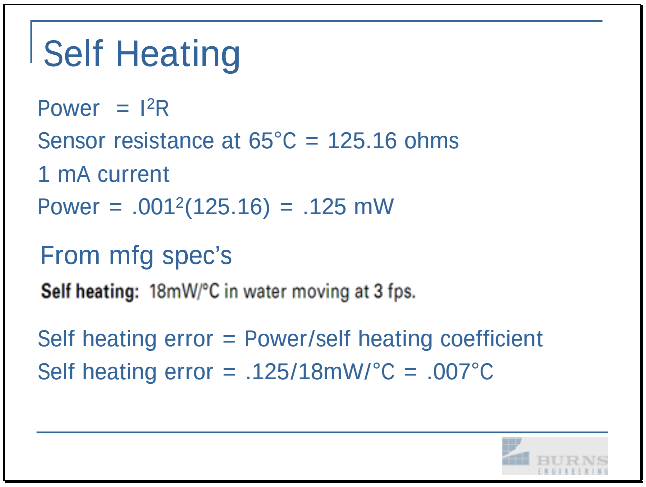
- If the process is at a steady state the hysteresis is zero
- If the process is cycling at greater than about 100°C then apply the mfg's specification.

Refer to the mfg specifications to determine a value. Generally the smaller the range the less hysteresis you will see. Our example is steady state so there is no hysteresis.



Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability	0.01	Mfg spec's
Repeatability	0.1	Mfg spec's
Thermal EMF	0.03	Test or mfg spec's
Hysteresis	0	Mfg spec's
Self Heating		
Time Response		
Stem Conduction		
Lead Wire		

These are a few other potential error sources. Application specific information is necessary to estimate the size of error.



Self Heating

Power = I^2R

Sensor resistance at 65°C = 125.16 ohms

1 mA current

Power = $.001^2(125.16)$ = .125 mW

From mfg spec's

Self heating: 18mW/°C in water moving at 3 fps.

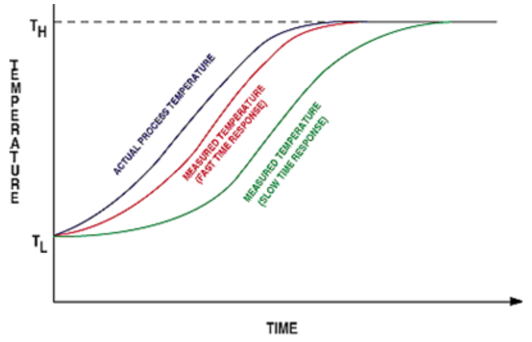
Self heating error = Power/self heating coefficient

Self heating error = .125/18mW/°C = .007°C

Any time a current is passed through a resistor heat is generated and it affects the PRT by causing an increase in resistance and is another small source of error. Most signal conditioning devices for RTDs use a current of 1 or 2 mA and for our example 1 mA is used.

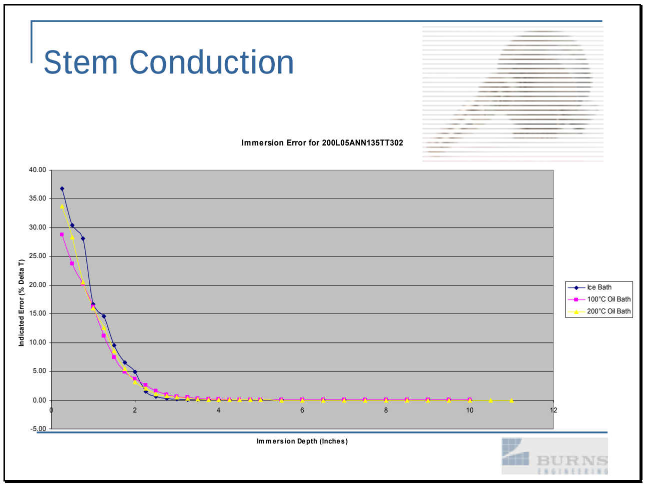
Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec’s
Stability	0.01	Mfg spec’s
Repeatability	0.1	Mfg spec’s
Thermal EMF	0.03	Test or mfg spec’s
Hysteresis	0	Mfg spec’s
Self Heating	0.007	Mfg spec’s
Time Response		
Stem Conduction		
Lead Wire		

Time Response



This graph shows the error when a slow response sensor is used in a rapidly changing process (T_L to T_H). For processes that change rapidly this can be a large error source. Our example is running at a steady state so the time constant error is zero.

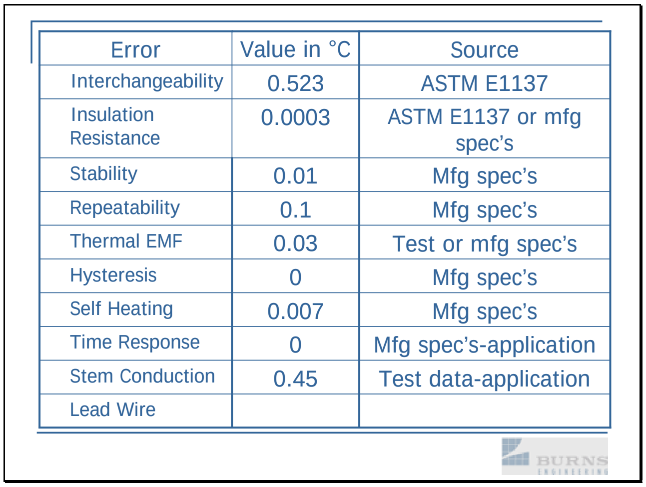
Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec’s
Stability	0.01	Mfg spec’s
Repeatability	0.1	Mfg spec’s
Thermal EMF	0.03	Test or mfg spec’s
Hysteresis	0	Mfg spec’s
Self Heating	0.007	Mfg spec’s
Time Response	0	Mfg spec’s-application
Stem Conduction		
Lead Wire		



Stem Conduction

Immersion Error for 200L05ANN135TT302

A thermowell and 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. Our example has a 2.5" immersion so estimating from the graph gives us an error of about 0.45°C which is our second largest error source behind interchangeability.



Error	Value in °C	Source
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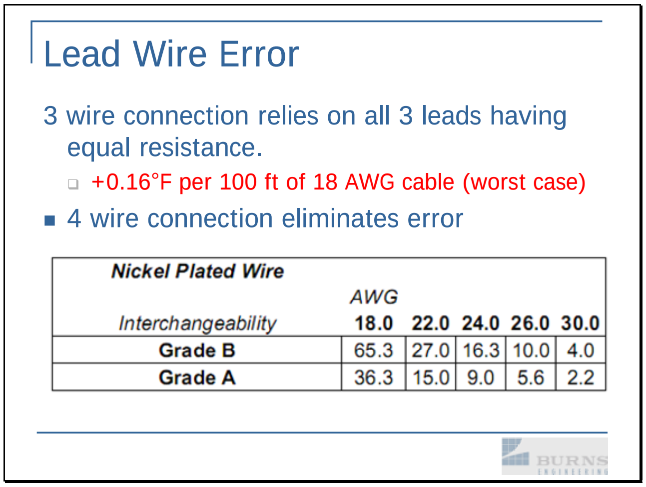
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability	0.01	Mfg spec's
Repeatability	0.1	Mfg spec's
Thermal EMF	0.03	Test or mfg spec's
Hysteresis	0	Mfg spec's
Self Heating	0.007	Mfg spec's
Time Response	0	Mfg spec's-application
Stem Conduction	0.45	Test data-application
Lead Wire		

These are a few other potential error sources. Application specific information is necessary to estimate the size of error.



Lead Wire Error

3 wire connection relies on all 3 leads having equal resistance.

- +0.16°F per 100 ft of 18 AWG cable (worst case)

- 4 wire connection eliminates error

Nickel Plated Wire

	AWG				
Interchangeability	**18.0**	**22.0**	**24.0**	**26.0**	**30.0**
Grade B	65.3	27.0	16.3	10.0	4.0
Grade A	36.3	15.0	9.0	5.6	2.2

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.

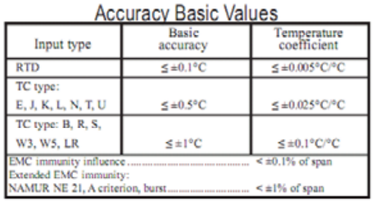
The table shows some maximum recommended cable lengths in feet to contain the lead wire error for the Grade A and Grade B sensors. As the wire size decreases so does the recommended cable length.

Error	Value in °C	Source
Interchangeability	0.523	ASTM E1137
Insulation Resistance	0.0003	ASTM E1137 or mfg spec's
Stability	0.01	Mfg spec's
Repeatability	0.1	Mfg spec's
Thermal EMF	0.03	Test or mfg spec's
Hysteresis	0	Mfg spec's
Self Heating	0.007	Mfg spec's
Time Response	0	Mfg spec's-application
Stem Conduction	0.45	Test data-application
Lead Wire	0	ASTM B193 + B355

Page 1 of the error chart is complete.

Temperature Transmitter

From mfg spec's

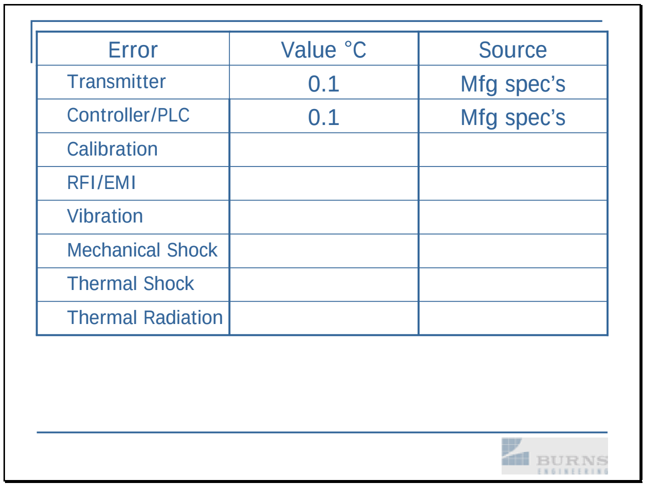


Accuracy Basic Values

Input type	Basic accuracy	Temperature coefficient
RTD	≤ ±0.1°C	≤ ±0.005°C/°C
TC type: E, J, K, L, N, T, U	≤ ±0.5°C	≤ ±0.025°C/°C
TC type: B, R, S, W3, W5, LR	≤ ±1°C	≤ ±0.1°C/°C
EMC immunity influence		< ±0.1% of span
Extended EMC immunity: NAMUR NE 21, A criterion, burst		< ±1% of span

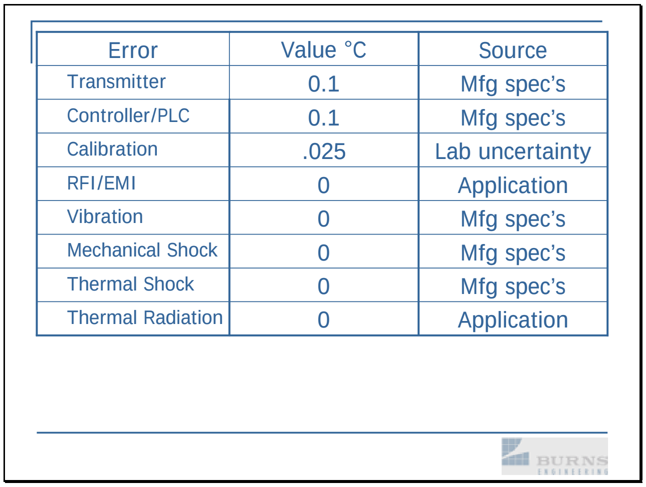
Our PRT is connected to a transmitter so we need to include the accuracy in our calculation. From the table for RTD input it is ± 0.1°C

Error	Value °C	Source
Transmitter	0.1	Mfg spec's
Controller/PLC		
Calibration		
RFI/EMI		
Vibration		
Mechanical Shock		
Thermal Shock		
Thermal Radiation		



Error	Value °C	Source
Transmitter	0.1	Mfg spec’s
Controller/PLC	0.1	Mfg spec’s
Calibration		
RFI/EMI		
Vibration		
Mechanical Shock		
Thermal Shock		
Thermal Radiation		

Reference the mfg spec’s for accuracy of your chart recorder, controller or other device.



Error	Value °C	Source
Transmitter	0.1	Mfg spec’s
Controller/PLC	0.1	Mfg spec’s
Calibration	.025	Lab uncertainty
RFI/EMI	0	Application
Vibration	0	Mfg spec’s
Mechanical Shock	0	Mfg spec’s
Thermal Shock	0	Mfg spec’s
Thermal Radiation	0	Application

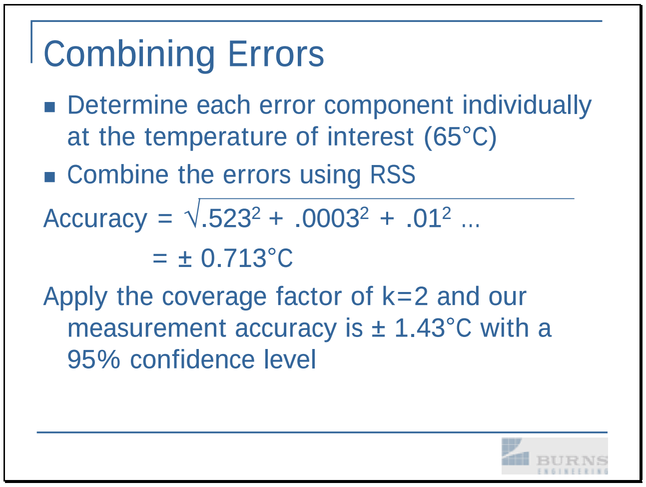
Next is calibration uncertainty. The RTD mfg’s lab has an uncertainty of 0.025°C for industrial grade sensors. We need to include this in our calculation if they have not already included it in their product specifications.

Next is RFI/EMI (radio frequency and electro magnetic interference). For our application the value is zero because we have a grounded metal housing around the PRT and transmitter. It’s usually a good idea to run shielded cable from the transmitter and ground the shield at the controller end, leaving the PRT end open.

Vibration will cause a PRT to drift faster than normal and we have to depend on the manufacturer to supply a value. The same for mechanical shock and thermal shock.

Thermal radiation is dependent on the installation. For our example we have no other heated equipment or radiation source located nearby so that value is also zero.

That completes our error table so the next step is to combine the errors.



Combining Errors

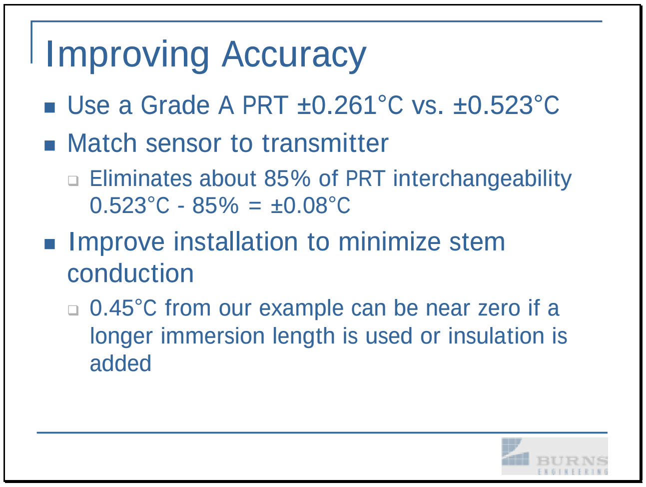
- Determine each error component individually at the temperature of interest (65°C)
- Combine the errors using RSS

Accuracy = $\sqrt{.523^2 + .0003^2 + .01^2 \ldots}$

$= \pm 0.713°C$

Apply the coverage factor of k=2 and our measurement accuracy is ± 1.43°C with a 95% confidence level

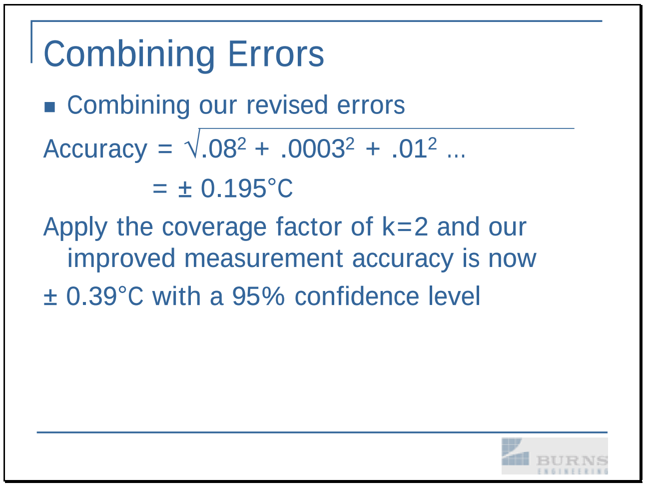
First we square all the errors and then add them together. Taking the square root of the sum results in 0.713°C. Then we apply our coverage factor which results in a measurement accuracy of ± 1.43°C. If you recall from our example specifications we were shooting for something better than 0.5°C. Now what?



Improving Accuracy

- Use a Grade A PRT ±0.261°C vs. ±0.523°C
- Match sensor to transmitter
  - Eliminates about 85% of PRT interchangeability 0.523°C - 85% = ±0.08°C
- Improve installation to minimize stem conduction
  - 0.45°C from our example can be near zero if a longer immersion length is used or insulation is added

Fortunately there are a few things we can do to improve accuracy. First is to choose a PRT with a tighter interchangeability. That will cut that error source in half. That’s still not enough though so we need to look at the next largest error source which was stem conduction. Adding insulation to the pipe will decrease it to near zero, or we can select a longer immersion length and install it into a tee to allow for more immersion. From our stem conduction graph we see that 4.5” will nearly eliminate the error. Those two changes may get us to 0.5°C however with another simple technique we can add a margin of certainty to our measurement. Matching the transmitter to the PRT will reduce the interchangeability error to about 0.08°C.
Entering the revised errors for interchangeability and stem conduction changes our measurement error to ± 0.195°C.



Combining Errors

- Combining our revised errors

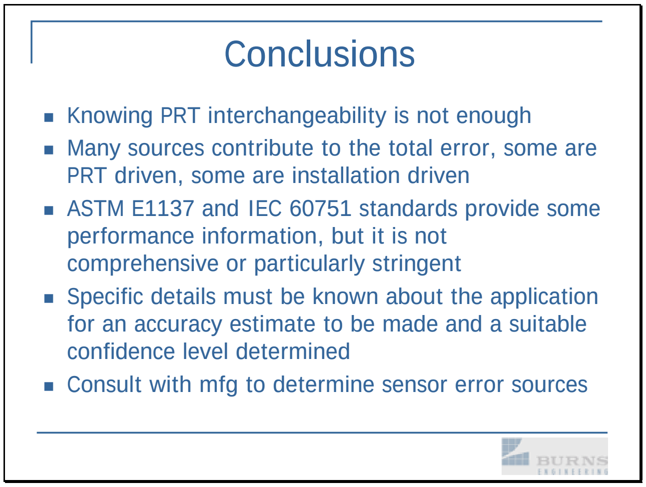
Accuracy = $\sqrt{.08^2 + .0003^2 + .01^2 \ldots}$

= ± 0.195°C

Apply the coverage factor of k=2 and our improved measurement accuracy is now

± 0.39°C with a 95% confidence level

Applying the coverage factor gives us ± 0.39°C which is now well within our ± 0.5°C target.



Conclusions

- Knowing PRT interchangeability is not enough
- Many sources contribute to the total error, some are PRT driven, some are installation driven
- ASTM E1137 and IEC 60751 standards provide some performance information, but it is not comprehensive or particularly stringent
- Specific details must be known about the application for an accuracy estimate to be made and a suitable confidence level determined
- Consult with mfg to determine sensor error sources

Questions?

Use the Q & A or chat window to send us a question.

Contact Bill later at 800-328-3871 ext. 13
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or visit www.burnsengineering.com

Thank you for attending!

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