Temperature Measurement Accuracy with RTDs
Session II: Significance and Management of Errors

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What we'll cover

Session 1: RTD Accuracy
- Terminology
- Error sources
  - Sensor
  - Installation
  - Instrumentation
  - Calibration

See the Presentation Notes at:
http://www.burnsengineering.com/rtdology/

What we'll cover

Session 2
- Significance of errors
- Managing errors
  - Rules of thumb
  - Sensor selection
  - Installation recommendations

What we'll cover

Session 3

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

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.

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.

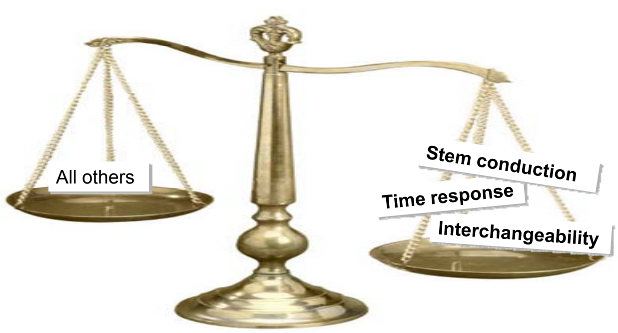
Other Sources

Other sources can produce errors but are difficult to analyze without installation unique information.

- Vibration
- Mechanical Shock
- Thermal Shock
- Thermal Radiation
- Nuclear Radiation

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

Significance of Errors



Three error sources far outweigh all the others in significance. Stem conduction, time response, and interchangeability are the largest.

Significance of Errors

Sensor
- Interchangeability
- Insulation resistance

Installation
- Stem conduction
- Time response
- Lead wire

Calibration

Instrumentation
- Transmitter
- Controller
- Recorder

Sensor Error

10

Interchangeability (largest component of sensor accuracy)

- Refers to the “closeness of agreement” in the resistance vs. temperature (R vs. T) relationship of a PRT to a pre-defined nominal R vs. T relationship.

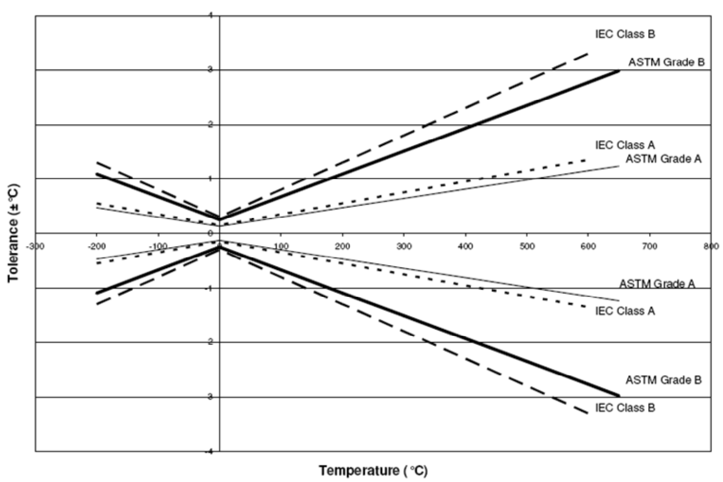
Table 1.1
Standard PRT Interchangeability Equations

Standard	Tolerance Nomenclature	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	Class A	$\pm [\,.15 + 0.002\,\lvert t \rvert\,]$
IEC 60751	Class B	$\pm [\,.3 + 0.005\,\lvert t \rvert\,]$

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

Two standards are in use that define the R vs. T relationship and within each there are two classes or grades of interchangeability.

Figure 1.1
Standard PRT Interchangeability



This graph shows the relationship between temperature and the interchangeability tolerance for each of the standards and classes. The ASTM Grade A has the tightest tolerance.

RTDs are manufactured to be100 ohms at 0°C. The two standards provide a common target for them to hit and the acceptable tolerances. As the temperature diverges from 0°C the tolerances increase.

Interchangeability

12

Design and manufacturing considerations are primary cause

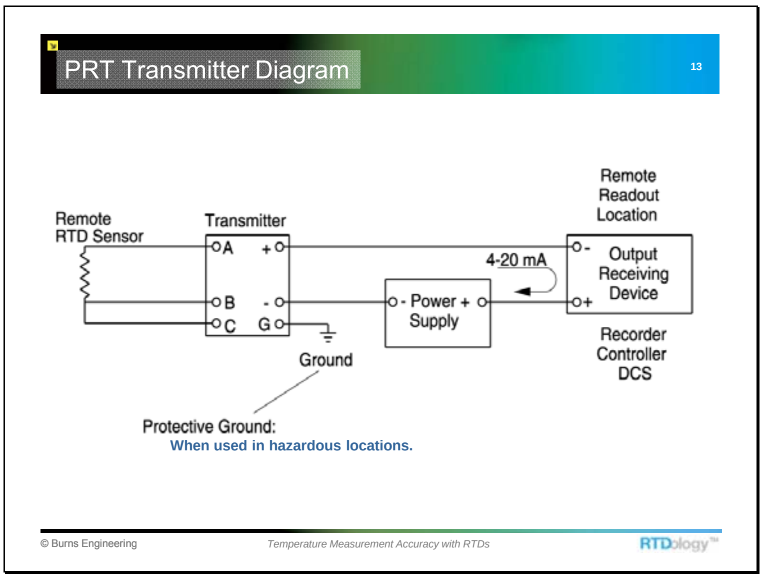
Reduce interchangeability error by:

- Selecting a PRT with tight interchangeability
- Performing a system calibration
  - Match transmitter to actual PRT R vs T

System calibrations are a good method to reduce interchangeability error. Placing the sensor in a known temperature bath while it is connected to the control device allows the output to be adjusted at the control device to match the bath temperature. About 85% of the interchangeability can be eliminated this way.

A second method to eliminate 85% of the interchangeability error in a measurement system is to use a PRT in conjunction with a transmitter that has matching capability. Transmitters with matching capability allow a specific R vs. T relationship to be entered into the transmitter software. In the case of an analog transmitter, the potentiometers for zero and span are adjusted to match the unique PRT resistance at the end points of the range. This method will nearly eliminate the interchangeability error. However, errors due to calibration and some external influence effects will still be present.

When the matched calibration option is specified there is no need to select a PRT with a tight interchangeability because the actual R vs. T relationship, which is determined by a comparison calibration, is used to calibrate the transmitter. A less expensive Grade B sensor can be specified. The table below shows the improvement in accuracy that can be achieved using this method.



Interchangeability

14

Matched transmitter example:

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

	Grade B	Grade A	Matched
PRT Tolerance at 121°C	±.76°C	.34	.05
Transmitter Accuracy	±.1°C	.1	.1
Combined System (RSS)	± .77°C	.35°C	.11°C

As you can see, matching is a very economical method to improve your system accuracy.

Interchangeability

BURNS ENGINEERING — **Report of Calibration** — NVLAP

Model:	12001-A-12-6-2-A
Serial Number:	841109
PO Number:	[illegible]
Description:	Platinum Resistance Thermometer, Secondary Standard
Calibration Procedure Numbers:	SOPC265 Rev B, SOPC267 Rev B, SOPC268 Rev A
Calibration Method:	Comparison to SPRT
Calibration Range:	-196°C to 420°C
Calibration Date:	2/16/2010
As-Found Condition:	New
As-Left Condition:	Calibrated
Customer:	

This platinum resistance thermometer (PRT) was calibrated using an AC bridge at a current of 1mA, at the temperatures reported below by comparison to Standard Platinum Resistance Thermometers (SPRTs). These SPRTs are calibrated to the International Temperature Scale of 1990 (ITS-90) and their calibration is traceable to the National Institute of Standards and Technology.

The combined standard uncertainty of this calibration includes all known sources present at the time of calibration. The uncertainties are reported at the calibration temperatures only, the uncertainties at intermediate temperatures can be computed from these values and the ITS-90 propagation of error curves. The combined standard uncertainty is multiplied by a coverage factor of 2 to give an expanded uncertainty, which defines the interval having a level of confidence of approximately 95 percent. The expanded uncertainty presented in this report is consistent with the 1993 ISO Guide to the Expression of Uncertainty in Measurement. The expanded uncertainty is not to be confused with a tolerance limit for the user during application.

Calibration Results

Temperature (deg C)	Resistance (ohms)	Uncertainty (mK)
-196.000	18.7506	± 24 mk
-38.000	84.7571	± 11 mk
0.010	99.9950	± 10 mk
200.000	177.2971	± 18 mk
420.000	256.9117	± 29 mk

ITS-90 Calibration Coefficients

R_{tpw} = 99.9950	a4 = -6.7833259E-4	b4 = -3.1074387E-5
	a8 = -7.2022759E-4	b8 = -7.9704873E-5

Comments and Limitations: None

The temperature calibration system used by Burns Engineering complies with the requirements of ANSI/NCSL Z540-1-1994, Part 1, and ISO/IEC 17025:2005. This calibration report applies only to the item calibrated. This report shall not be used to claim certification, approval, or endorsement by NVLAP, NIST, or any agency of the federal government.

Environmental conditions:
The ambient conditions of the laboratory are controlled to 21 ± 4 degrees C and 80% maximum relative humidity.

The following measuring and test equipment were used in this calibration:

Item	Model	Serial Number	Recall Date
SPRT	8163Q8	1873681	5/25/2010
SPRT	162CE	4417	1/30/2012

Resistance information is available from a calibration certificate for the sensor to be matched. Some transmitters will accept the temperature coefficients generated from a full calibration and provide the best accuracy match.

Interchangeability

Resistance vs. Temperature table using ITS-90 coefficients for RTD Serial Number: 841109
Coefficients used: Ro1: 99.995 a4: -6.7833259E-04 b4: -3.1074387E-05 a8: -7.2022759E-04 b8: -7.9704873E-05
Temperatures are in deg Celcius

	-0	-1	-2	-3	-4	-5	-6	-7	-8	-9	
-200	17.0261										-200
-190	21.3498	20.9160	20.4824	20.0490	19.6159	19.1830	18.7506	18.3186	17.8871	17.4563	-190
-180	25.6882	25.2547	24.8211	24.3874	23.9536	23.5197	23.0857	22.6517	22.2177	21.7837	-180
-170	30.0104	29.5793	29.1480	28.7164	28.2845	27.8523	27.4200	26.9873	26.5545	26.1214	-170
-160	34.3045	33.8765	33.4482	33.0195	32.5906	32.1613	31.7317	31.3019	30.8717	30.4412	-160
-150	38.5674	38.1425	37.7173	37.2918	36.8660	36.4399	36.0134	35.5867	35.1596	34.7322	-150
-140	42.8000	42.3780	41.9558	41.5333	41.1104	40.6873	40.2639	39.8403	39.4163	38.9920	-140
-130	47.0047	46.5854	46.1658	45.7460	45.3260	44.9056	44.4850	44.0642	43.6431	43.2217	-130
-120	51.1842	50.7673	50.3502	49.9328	49.5152	49.0974	48.6794	48.2611	47.8425	47.4237	-120
-110	55.3413	54.9265	54.5116	54.0964	53.6810	53.2654	52.8496	52.4336	52.0174	51.6009	-110
-100	59.4780	59.0652	58.6522	58.2390	57.8256	57.4120	56.9983	56.5843	56.1702	55.7558	-100
-90	63.5961	63.1851	62.7739	62.3625	61.9510	61.5393	61.1274	60.7153	60.3030	59.8906	-90
-80	67.6972	67.2878	66.8783	66.4686	66.0587	65.6487	65.2385	64.8282	64.4177	64.0070	-80
-70	71.7823	71.3745	70.9665	70.5584	70.1501	69.7417	69.3331	68.9244	68.5155	68.1064	-70
-60	75.8524	75.4460	75.0395	74.6329	74.2261	73.8192	73.4121	73.0049	72.5975	72.1900	-60
-50	79.9081	79.5032	79.0981	78.6929	78.2875	77.8820	77.4764	77.0706	76.6647	76.2586	-50
-40	83.9502	83.5466	83.1429	82.7390	82.3350	81.9309	81.5266	81.1222	80.7176	80.3130	-40
-30	87.9792	87.5769	87.1744	86.7718	86.3691	85.9663	85.5634	85.1603	84.7571	84.3537	-30
-20	91.9954	91.5944	91.1932	90.7919	90.3904	89.9889	89.5872	89.1854	88.7834	88.3814	-20
-10	95.9993	95.5995	95.1995	94.7994	94.3992	93.9989	93.5985	93.1979	92.7972	92.3964	-10
0	99.9911	99.5924	99.1937	98.7948	98.3958	97.9967	97.5975	97.1981	96.7986	96.3991	0
	-0	-1	-2	-3	-4	-5	-6	-7	-8	-9	

Significance of Errors

Sensor
- Interchangeability
- Insulation resistance

Installation
- Stem conduction
- Time response
- Lead wire

Calibration

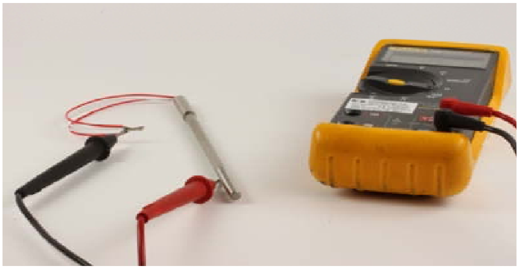
Instrumentation
- Transmitter
- Controller
- Recorder

Insulation Resistance Error

18

Insulation resistance

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



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An important electrical check that should be performed as part of any calibration. The test is performed with 50 or 100 VDC applied between the leads and sheath.

Some manufacturers use 500 VDC and 500 or 1000 megohms as a minimum at room temperature.

Insulation Resistance

19

Standard	Temp (°C)	Min. IR (MΩ)	Estimated Error (100 ohm PRT(°C))
ASTM E1137	25	100	.0003
ASTM E1137	300	10	.0130
ASTM E1137	650	2	.1700
IEC 60751	25	100	.0003
IEC 60751	100 to 300	10	.0130
IEC 60751	301 to 500	2	.1200
IEC 60751	501 to 850	.5	1.0000

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IR decreases with an increase in temperature and that's why manufacturing specifications are set high at room temperature where the test is performed.

Low IR can cause a significant error. Laboratory standards may have IR of 1000 megohms or may be measured in the terraohm range. Higher is better.

Insulation Resistance

20

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

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Several sources can cause low IR. Most common is moisture leaking into the sensor. It may be trapped during manufacture and cause variations in IR as the moisture moves around inside the probe. Sometimes the sensor may be dried out by placing it in an oven and heating for several hours. The sensor should be checked frequently to insure that moisture did not leak back in.

Insulation Resistance

Ways to minimize

- PRT is designed properly for the application
  - Moisture seal can handle thermal/mechanical environment
- Early detection of problems
  - Measure IR often
  - >200 megohms at 20°C

Most important is to make sure the sensor is designed to meet the rigors of the application. One of the most difficult applications is monitoring temperature inside a steam autoclave. When the chamber is evacuated, any air inside the sensor can leak out, and then when steam is introduced it goes right inside the sensor and you have low IR. A properly sealed sensor will prevent this “breathing” and insure a long and accurate life.

Significance of Errors

Sensor
- Interchangeability
- Insulation resistance

Installation
- Stem conduction
- Time response
- Lead wire

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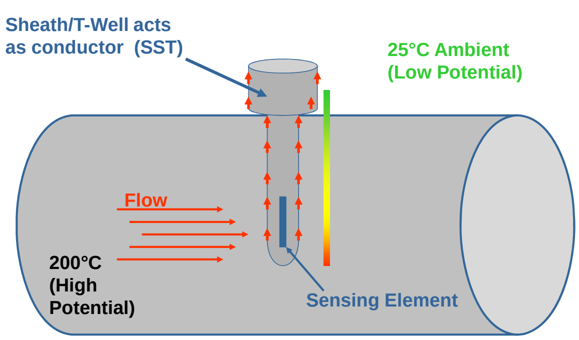
Stem Conduction

Heat conduction along sheath or lead wires of probe or thermowell



The external parts of the sensor act like a radiator having a chilling effect on the sensing element. Pathways are from the metal sheath, internal leadwires, and even the potting material.

Stem Conduction

24

To minimize

- Choose the right sensor
- Use a sensor / thermowell that has sufficient immersion into the process 10 x sheath diameter plus sensitive length
  - 3.5" for .25 sheath and 1" sensitive length
  - 1.5" for .125 sheath.
- Insulate the exterior portion to isolate it from ambient conditions
- Use special tip sensitive designs
- Consult manufacturer for appropriate sensor

The immersion length rule works well for direct immersion style sensors.

Thermowell assemblies act a little differently as will be seen in the upcoming graph.

Sensor design also has a large influence on stem conduction. Smaller diameters, low mass, non-heat conductive materials will help to minimize stem conduction.

Stem Conduction

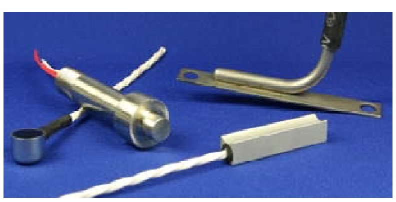
25

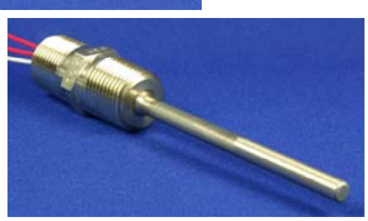
- Difficult to analyze, can be very sensitive to depth.
- Heat transfer conditions heavily influence the rule.
- Error directly proportional to ΔT

Because there are so many variables an actual error value can be difficult to determine. Process fluid characteristics, flow rate and ambient conditions are just a few of the variables.

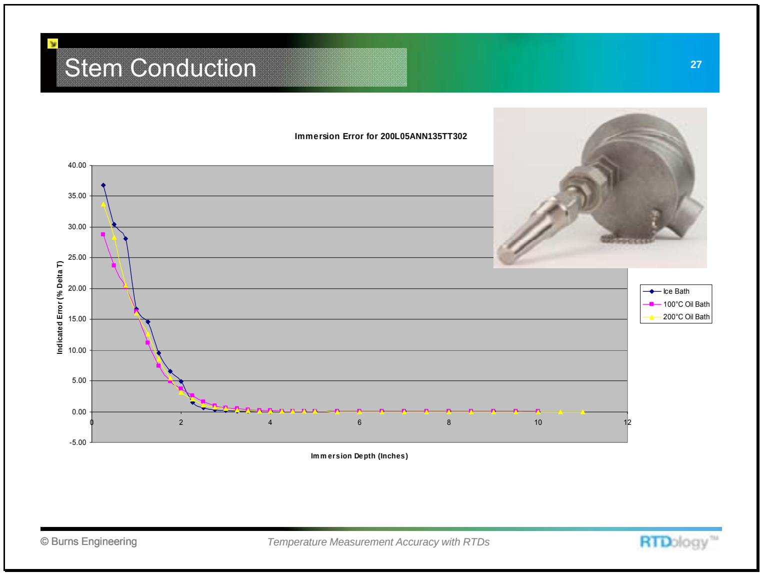
Stem Conduction

26

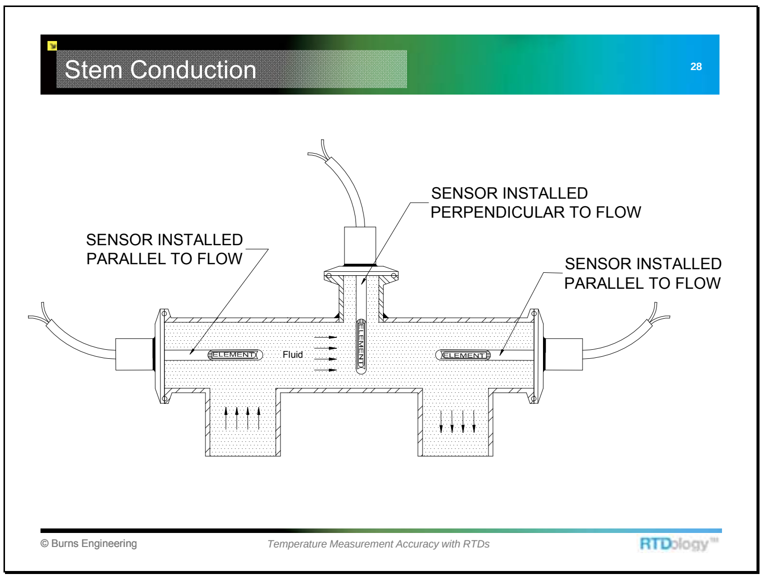




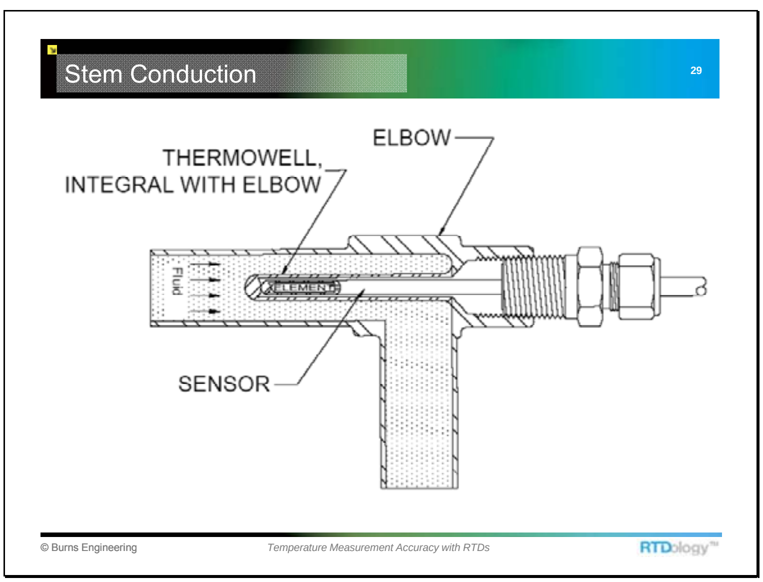
There are many styles of surface mount sensors and each has a preferred mounting method. Whether bolted, strapped, or glued on, the accuracy of each suffers from the effects of the ambient conditions and mounting location. Each requires external insulation to isolate it from ambient conditions. The immersion styles are less affected by stem conduction.



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.



Installation into a tee with the sensor parallel to the flow can allow for longer immersion length and minimal stem conduction. The sensor on the right is the preferred installation method.



A special elbow fitting with an integral thermowell allows for sufficient immersion length in tubes down to 0.5” diameter.

Stem Conduction

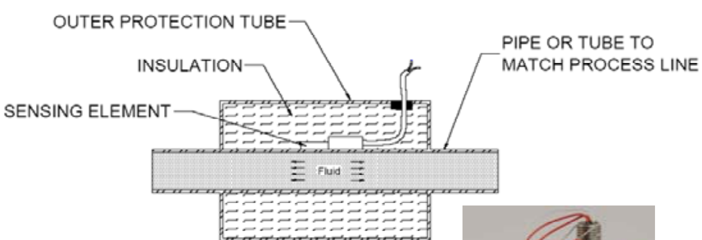
30

In tubes smaller than 1” the tube is flared to allow for the thermowell without constricting flow through the elbow.

Stem Conduction

31

Non-intrusive



A non-intrusive is a hybrid surface mount sensor where the insulation and mechanical protection is built-in. This design still shows some conduction error because insulation is not 100% efficient and with a surface mount the pipe temperature is being measured and not the actual fluid.

This style sensor is useful for small tubes or where the product is viscous or sticky and would build up on an immersion sensor.

Significance of Errors

32

- Sensor
  - Interchangeability
  - Insulation resistance
- Installation
  - Stem conduction
  - Time response
  - Lead wire
- Calibration
- Instrumentation
  - Transmitter
  - Controller
  - Recorder

Time Response

Time Response

- Getting the sensor to follow as close to the process as possible
- Time constant – time required for the sensor to respond to 63.2% of a step change in temperature while in water moving at 3 fps

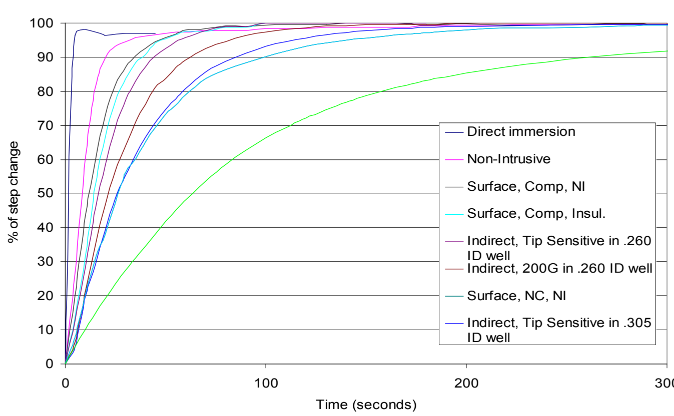
The time response provides a standard method for comparing the relative “quickness” of each style sensor. The test starts with the sensor in 0°C water and then placed in room temperature water moving at 3 fps.

Time Response

- The less thermal resistance between the sensor and the process, the better
- Smaller diameter probes
- Direct Immersion or special fast tip thermowell

The fast response tip thermowell has a time constant of 4 seconds which equals that of a 0.25” diameter direct immersion sensor.

Time Response

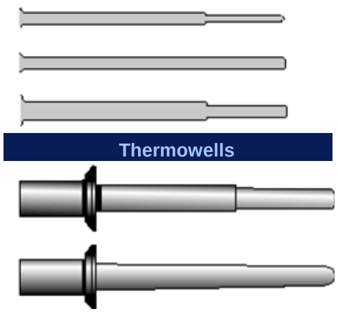


This graph compares the time response of several styles of sensors. The fastest is the direct immersion style and the surface mount the slowest.

Time Response

36

TIME RESPONSE	Direct Immersion RTD's	DIAMETERS
2.5 seconds		1/4" - 1/8"
5.5 seconds		1/4"
		3/8" - 1/4"
TIME RESPONSE with HTC	Thermowells	
22/11 seconds		Reduced Tip
26/11 seconds		Tapered



Addition of heat transfer compound (HTC) can improve the time response of thermowell/RTD assemblies.

Significance of Errors

37

- Sensor
  - Interchangeability
  - Insulation resistance
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  - Stem conduction
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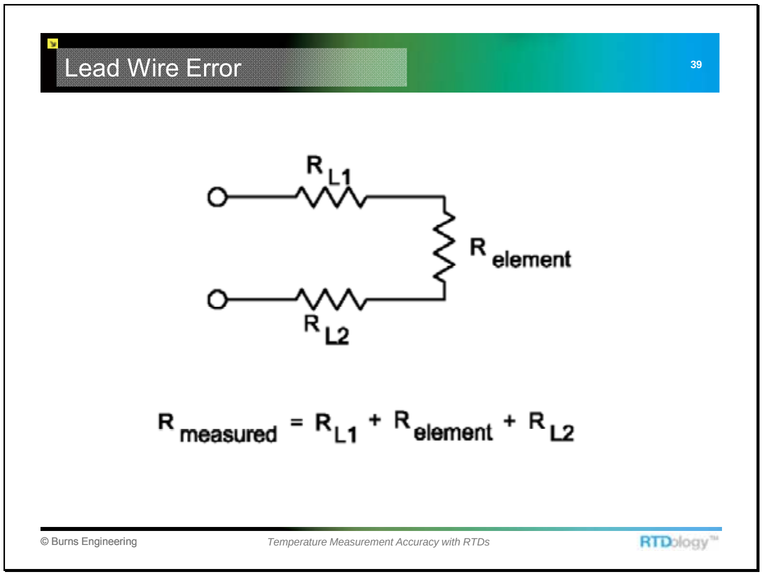
Lead Wire Error

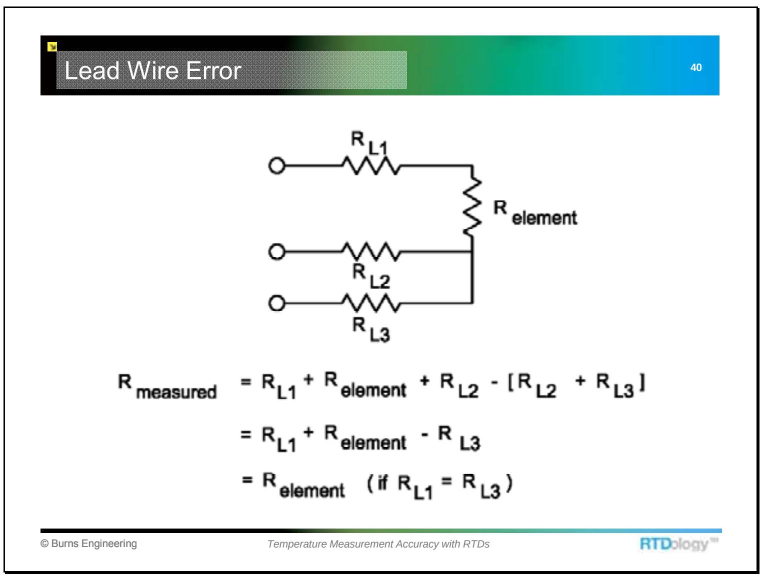
38

- 2 wire connection adds lead resistance in series with PRT element.
- 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

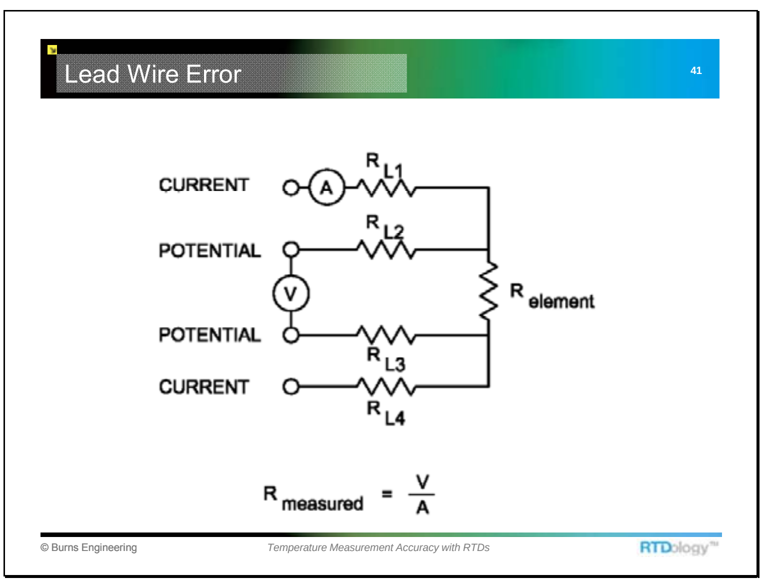
Lead wires used to connect the sensor to a process control instrument can cause a measurement error. Two and three wire circuits have the largest errors and the 4 wire will nearly eliminate the error.



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



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.

Significance of Errors

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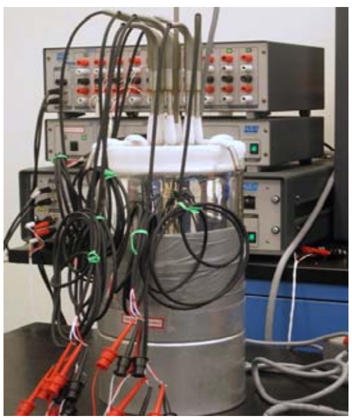
Calibration Errors



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 Errors

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

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

Calibration Errors

To minimize:

- Obtain a high quality/accuracy calibration for the sensor
- Calibrate sensors at the correct intervals

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- Insulation resistance

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Significance of Errors

Transmitter accuracy spec

Accuracy General Values

Input Type	Absolute Accuracy	Temperature Coefficient
All	≤ ±0.05% of span*	≤ ±0.01% of span* / °C

Accuracy Basic Values

Input Type	Basic Accuracy	Temperature Coefficient
RTD	≤ ±0.2°C	≤ ±0.01°C/°C
TC type: E, J, K, L, N, T, U	≤ ±1°C	≤ ±0.05°C/°C
TC type: B, R, S, W3, W5, LR	≤ ±2°C	≤ ±0.2°C/°C
EMC immunity influence	< ±0.5% of span	
Extended EMC immunity:		
NAMUR NE 21, A criterion, burst........	< ±1% of span	

Instrument specifications need to be reviewed carefully to be sure you have all the error sources identified for your application. Ambient temperature can affect the accuracy.

Summary

- Many sources contribute to the total error, some are PRT driven, some are application 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.

Summary

- Understand the sources of error and focus on the most significant
- Identify the uncertainty that is present
- Reduce factors that contribute to the error
  - Installation
  - Sensor selection
  - Calibration
  - Instrumentation
  - Environment
- Determine what the acceptable level of error is for your application and select materials based on those decisions

I think the most important thing to take away from this session is the need to match the sensor design to your process and installation detail. The larger errors are usually caused by the installation or using a sensor not designed for the application.

Questions?

Use the chat window to send us a question now

Contact us later at 800-328-3871
bbergquist@burnsengineering.com
952-567-6413

or
visit us at www.burnsengineering.com

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Watch for upcoming RTDology™ events

Temperature Measurement Accuracy with RTDs

- Session III: Calculating Measurement Error

Measuring Temperature in Small Diameter Lines

Thank You for Attending

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