

Signal Conditioning and Linearization of RTD Sensors

Collin Wells

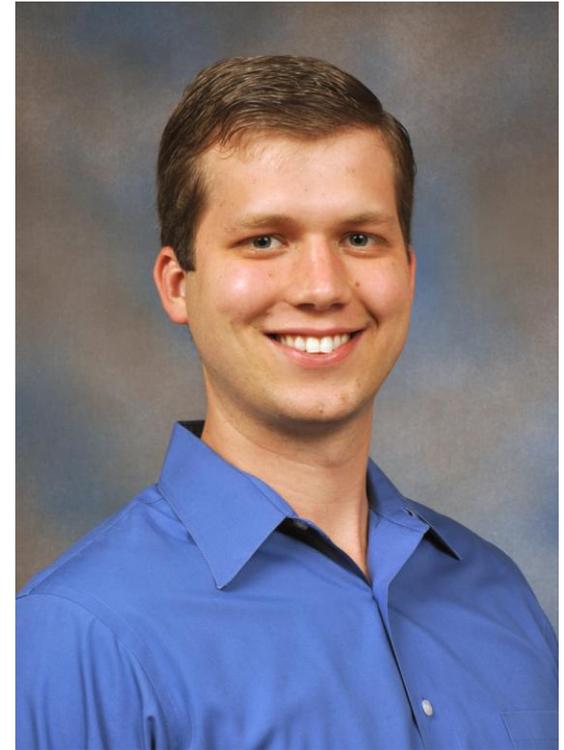
Texas Instruments

HPA Precision Linear Applications

9/24/11

Introduction

- Primary Support
 - 4-20mA Loop Drivers (XTRXXX)
 - Gamma Buffers (BUFXXXXX)
- Other Support
 - Temperature Sensors (TMP)
 - IR Temperature Sensors (TMP006)
 - OPA Stability
 - Instrument Amplifiers
- Applications (Other)
 - Industrial – Programmable Logic Controllers (PLC)
 - RTD
 - Reference Designs

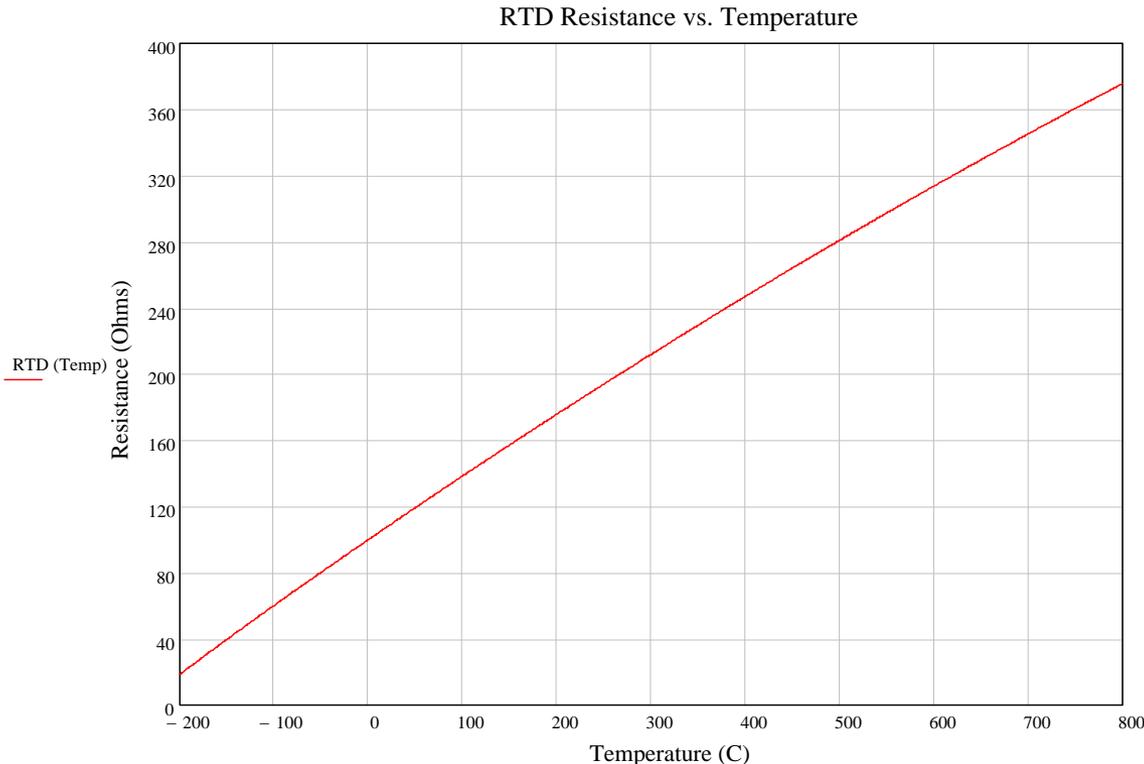
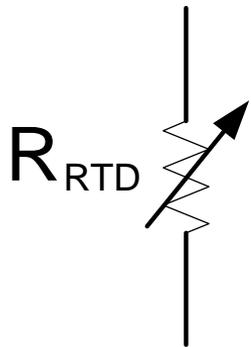


Contents

- RTD Overview
- RTD Nonlinearity
- Analog Linearization
- Digital Acquisition and Linearization

What is an RTD?

- Resistive Temperature Detector
- Sensor with a predictable resistance vs. temperature
- Measure the resistance and calculate temperature based on the Resistance vs. Temperature characteristics of the RTD material



PT100
 $\alpha = 0.00385$

How does an RTD work?

$$\text{Resistance} = R = \frac{\rho \cdot L}{A}$$

$$\text{Resistivity} = \rho = \frac{1}{e \cdot n \cdot \mu}$$

- L = Wire Length
- A = Wire Area
- e = Electron Charge (1.6e-19 Coulombs)
- n = Electron Density
- u = Electron Mobility

- The product $n \cdot u$ decreases over temperature, therefore resistance increases over temperature (PTC)
- Linear Model of Conductor Resistivity Change vs. Temperature

$$\rho(t) = \rho_0 \left(1 + \alpha(t - t_0) \right)$$

What is an RTD made of?

- Platinum (pt)
- Nickel (Ni)
- Copper (Cu)
- Have relatively linear change in resistance over temp
- Have high resistivity allowing for smaller dimensions
- Either Thin-Film or Wire-Wound

Metal	Resistivity (Ohm/CMF)
Gold (Au)	13
Silver (Ag)	8.8
Copper (Cu)	9.26
Platinum (Pt)	59
Tungsten (W)	30
Nickel (Ni)	36

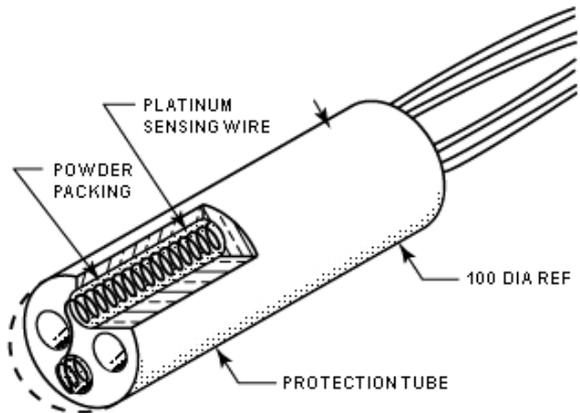


Figure 1. The coiled element sensor, made by inserting the helical sensing wires into a packed powder-filled insulating mandrel, provides a strain-free sensing element.

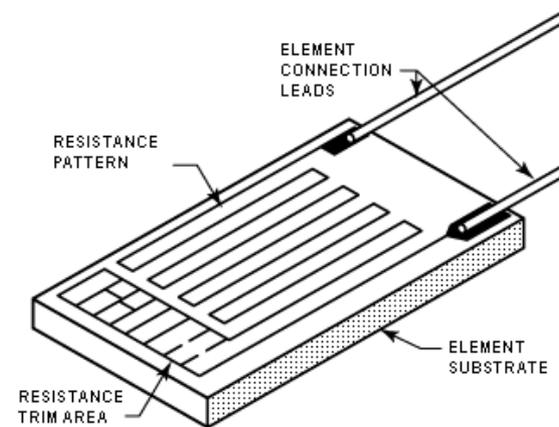


Figure 2. The thin film sensing element is made by depositing a thin layer of platinum in a resistance pattern on a ceramic substrate. A glassy layer is applied for seal and protection.

*Images from RDF Corp

How Accurate is an RTD?

- Absolute accuracy is “Class” dependant - defined by DIN-IEC 60751. Allows for easy interchangeability of field sensors

Tolerance Class (DIN-IEC 60751)	**Temperature Range of Validity		Tolerance Values (C)	Resistance at 0C (Ohms)	Error at 100C (C)	Error over Wire-Wound Range (C)
	Wire-Wound	Thin-Film				
*AAA (1/10 DIN)	0 - +100	0 - +100	+/- (0.03 + 0.0005*t)	100 +/- 0.012	0.08	0.08
AA (1/3DIN)	-50 - +250	0 - +150	+/- (0.1 + 0.0017*t)	100 +/- 0.04	0.27	0.525
A	-100 - +450	-30 - +300	+/- (0.15 + 0.002*t)	100 +/- 0.06	0.35	1.05
B	-196 - +600	-50 - +500	+/- (0.3 + 0.005*t)	100 +/- 0.12	0.8	3.3
C	-196 - +600	-50 - +600	+/- (0.6 + 0.01*t)	100 +/- 0.24	1.6	6.6

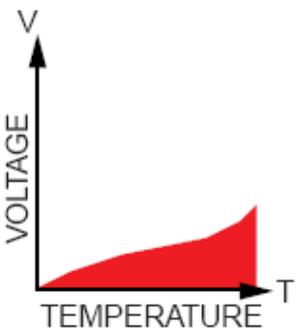
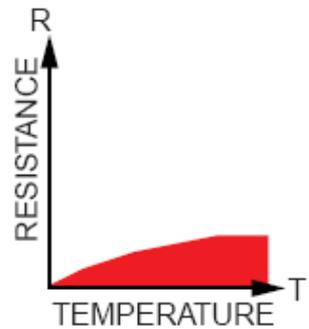
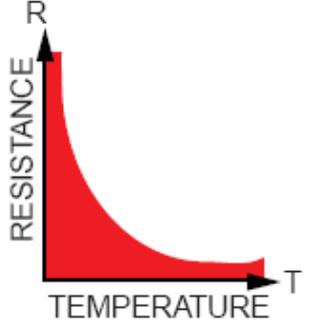
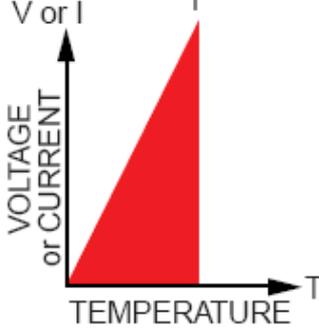
*AAA (1/10DIN) is not included in the DIN-IEC-60751 spec but is an industry accepted tolerance class for high-performance measurements

**Manufacturers may choose to guarantee operation over a wider temperature range than the DIN-IEC60751 provides

- Repeatability usually very good, allows for individual sensor calibration
- Long-Term Drift usually <0.1C/year, can get as low as 0.0025C/year

Why use an RTD?

Table Comparing Advantages and Disadvantages of Temp Sensors

	Thermocouple  	RTD  	Thermistor  	I. C. Sensor  
Advantages	<input type="checkbox"/> Self-powered <input type="checkbox"/> Simple <input type="checkbox"/> Rugged <input type="checkbox"/> Inexpensive <input type="checkbox"/> Wide variety <input type="checkbox"/> Wide temperature range	<input type="checkbox"/> Most stable <input type="checkbox"/> Most accurate <input type="checkbox"/> More linear than thermocouple	<input type="checkbox"/> High output <input type="checkbox"/> Fast <input type="checkbox"/> Two-wire ohms measurement	<input type="checkbox"/> Most linear <input type="checkbox"/> Highest output <input type="checkbox"/> Inexpensive
Disadvantages	<input type="checkbox"/> Non-linear <input type="checkbox"/> Low voltage <input type="checkbox"/> Reference required <input type="checkbox"/> Least stable <input type="checkbox"/> Least sensitive	<input type="checkbox"/> Expensive <input type="checkbox"/> Current source required <input type="checkbox"/> Small ΔR <input type="checkbox"/> Low absolute resistance <input type="checkbox"/> Self-heating	<input type="checkbox"/> Non-linear <input type="checkbox"/> Limited temperature range <input type="checkbox"/> Fragile <input type="checkbox"/> Current source required <input type="checkbox"/> Self-heating	<input type="checkbox"/> $T < 200^\circ\text{C}$ <input type="checkbox"/> Power supply required <input type="checkbox"/> Slow <input type="checkbox"/> Self-heating <input type="checkbox"/> Limited configurations

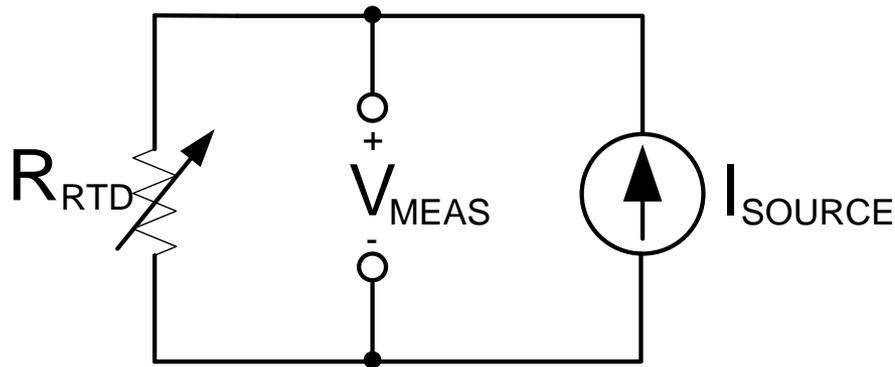
How to Measure an RTD Resistance?

- Use a.....

Current Source

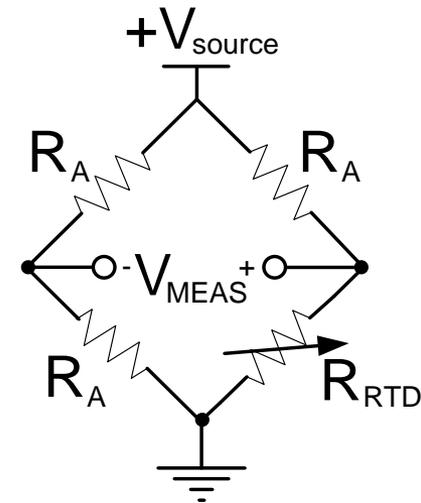
or

Wheatstone Bridge



$$V_{meas} = I_{source} \cdot R_{RTD}$$

$$R_{RTD} = \frac{V_{meas}}{I_{source}}$$



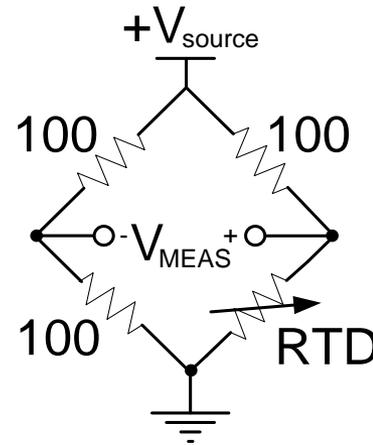
$$V_{meas} = V_{source} \cdot \left[\left(\frac{R_{RTD}}{R_A + R_{RTD}} \right) - \frac{1}{2} \right]$$

$$R_{RTD} = \frac{2 \cdot R_A \cdot V_{meas} + R_A \cdot V_{source}}{V_{source} - 2 \cdot V_{meas}}$$

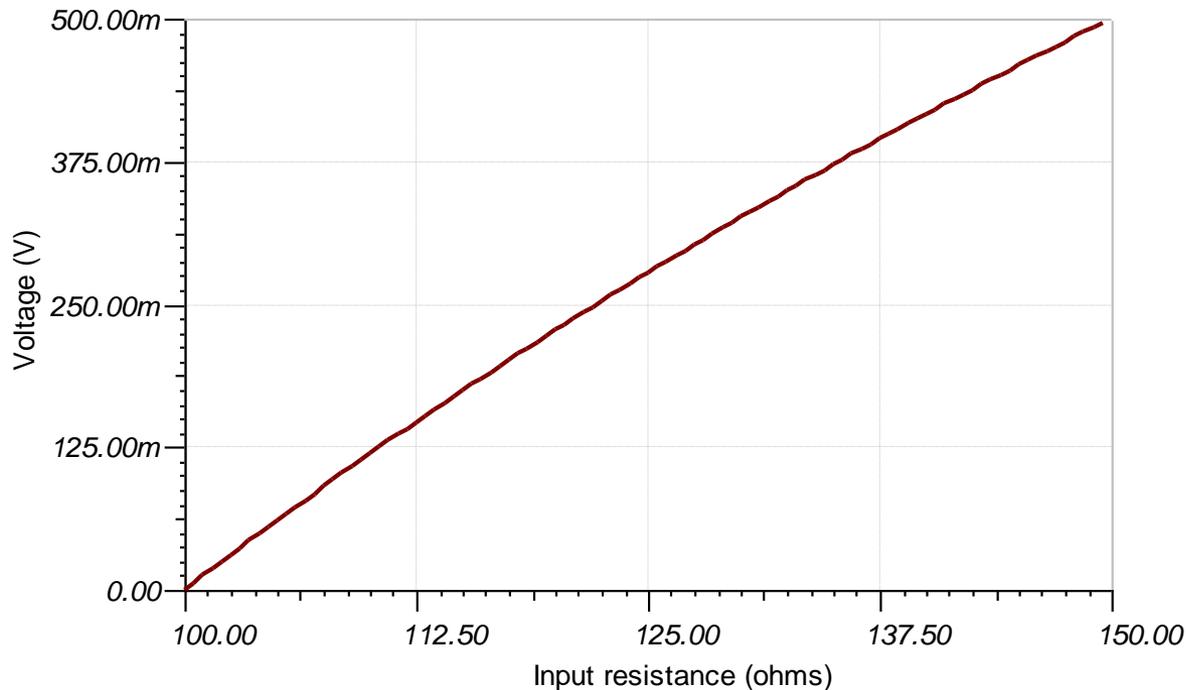
Note on Non-Linear Output of Bridge

$$V_{\text{meas}} = V_{\text{source}} \cdot \left[\left(\frac{R_{\text{RTD}}}{R_A + R_{\text{RTD}}} \right) - \frac{1}{2} \right]$$

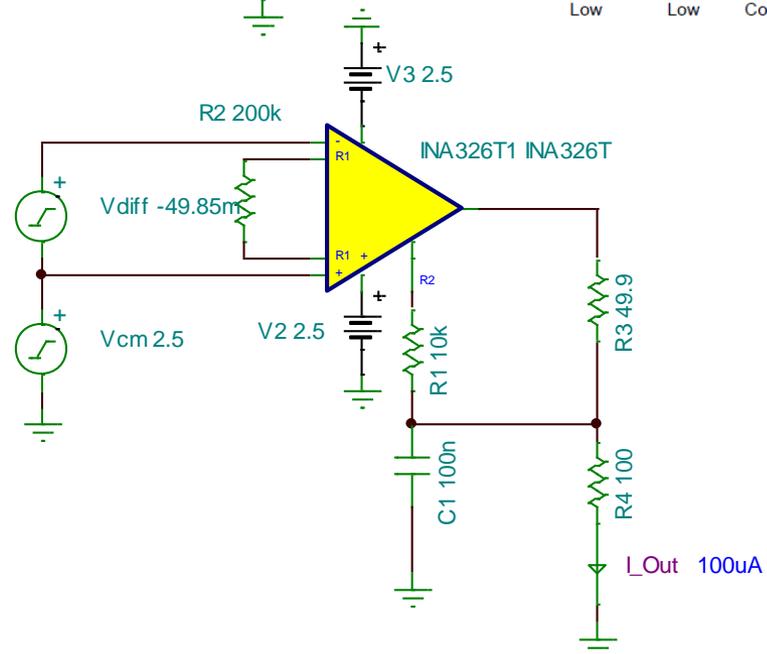
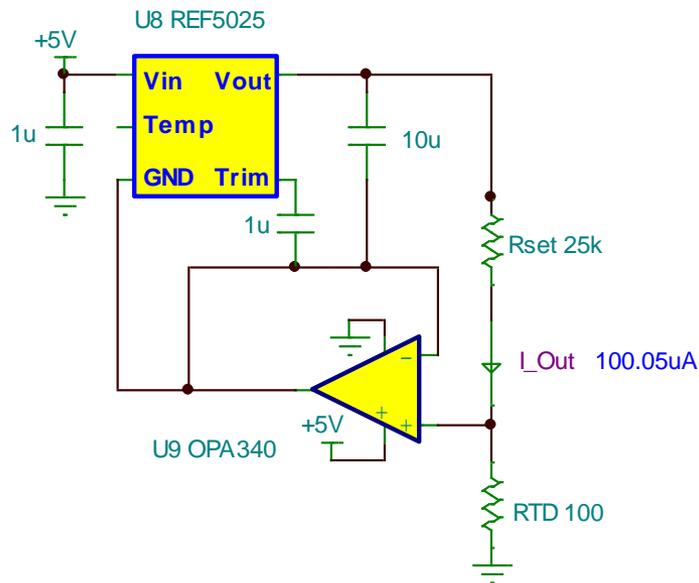
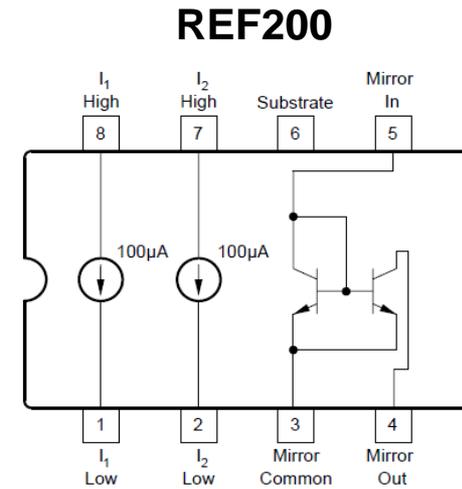
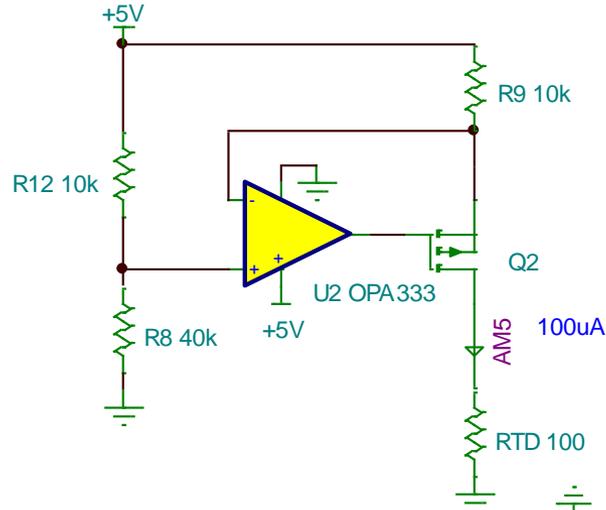
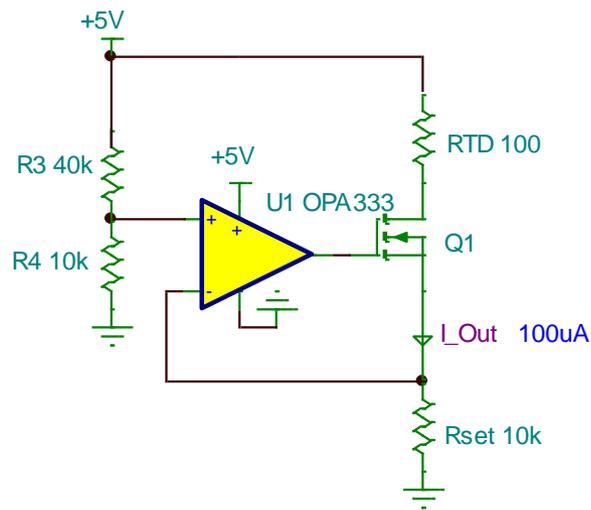
Denominator causes a non-linear output even for a linear sensor



$\Delta\text{RTD} = 50\text{ohms}$

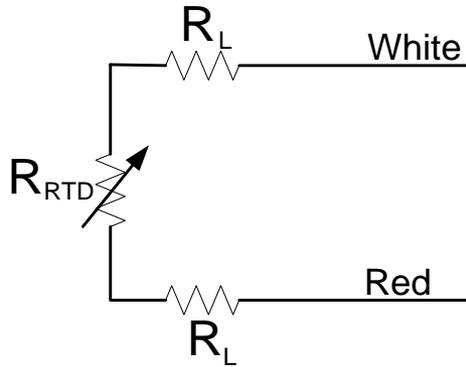


Simple Current Source / Sink Circuits

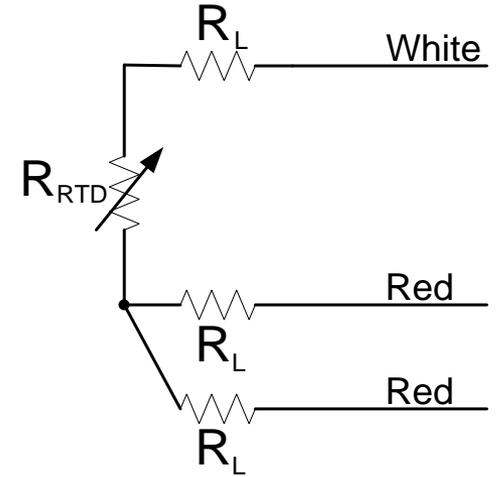


RTD Types and Their Parasitic Lead Resistances

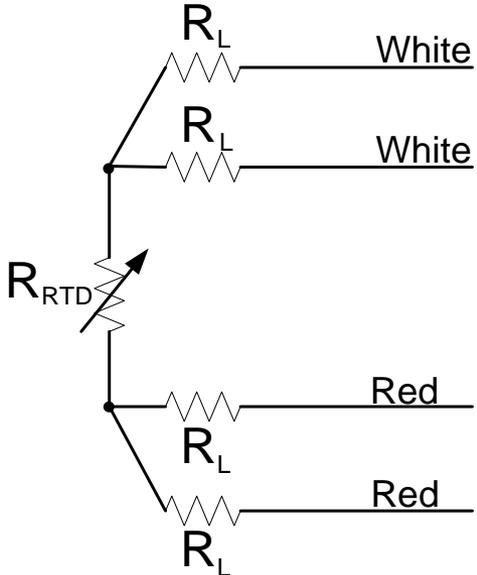
2-Wire



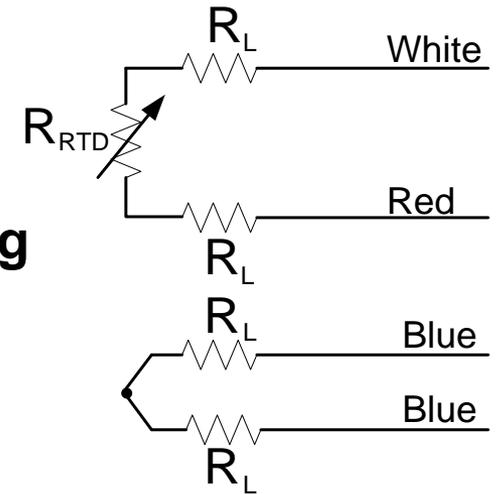
3-Wire



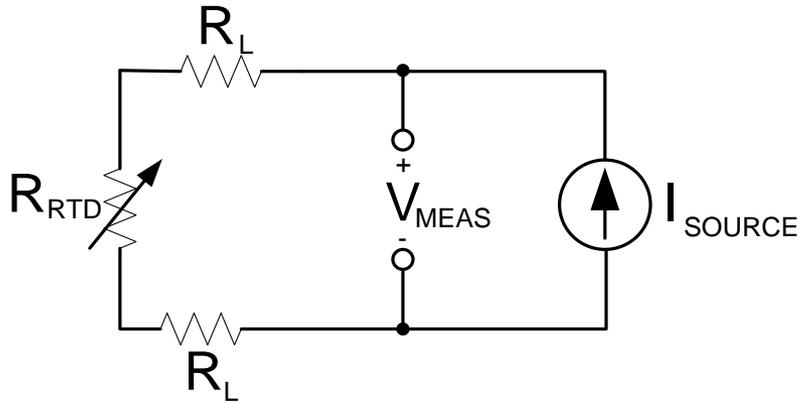
4-Wire



**2-Wire with
Compensating
Loop**

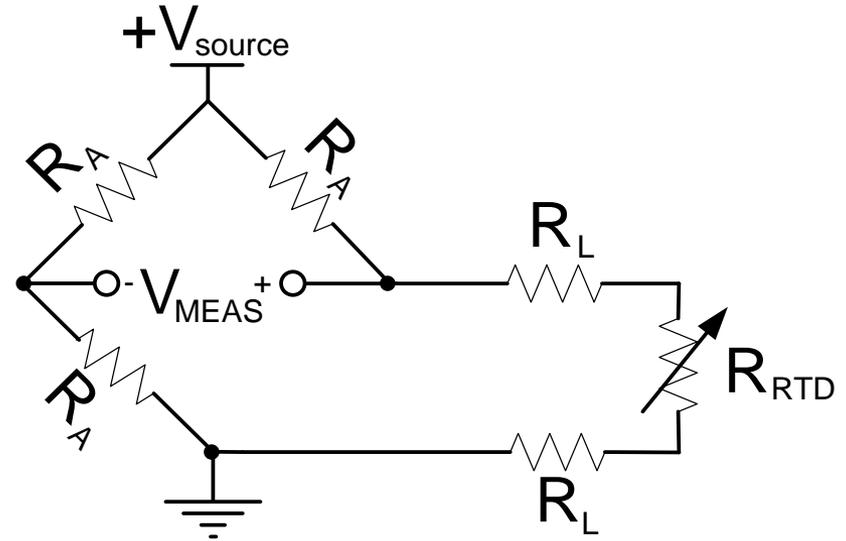


2-Wire Measurements



$$V_{meas} = I_{source} \cdot R_{RTD} + I_{source} \cdot 2 \cdot R_L$$

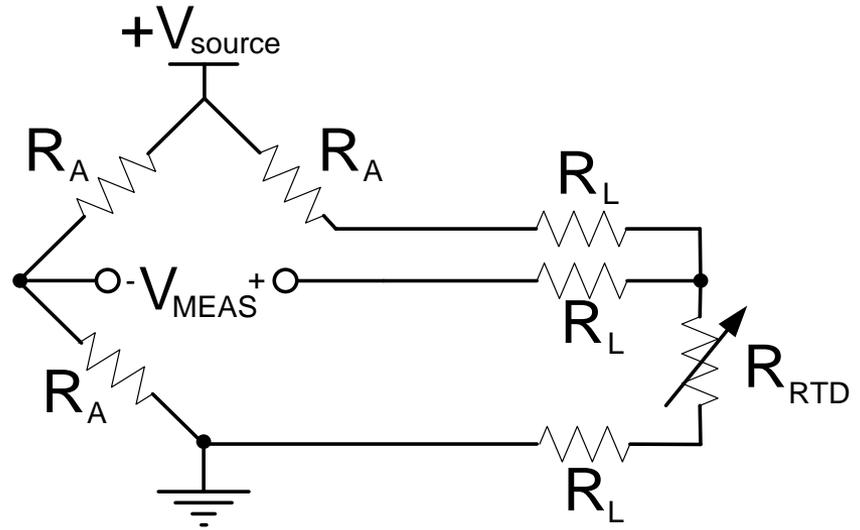
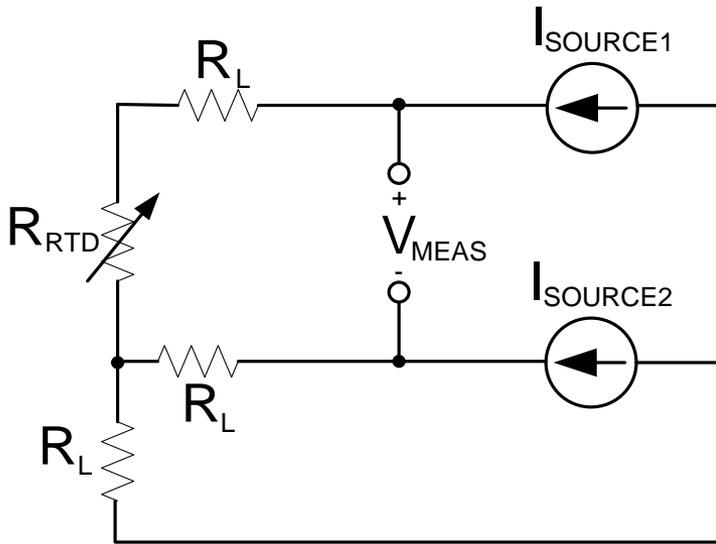
$$\text{Error} = I_{source} \cdot 2R_L$$



$$V_{meas} = V_{source} \cdot \left[\left(\frac{R_{RTD} + 2R_L}{R_A + R_{RTD} + 2R_L} \right) - \frac{1}{2} \right]$$

$$\text{Error} = V_{source} \cdot \left[\frac{2 \cdot R_A \cdot R_L}{(R_A + R_{RTD}) \cdot (R_A + 2 \cdot R_L + R_{RTD})} \right]$$

3-Wire Measurements



$$I_{\text{source1}} = I_{\text{source2}} = I$$

$$V_{\text{meas}_+} = I \cdot R_L + I \cdot R_{\text{RTD}} + (2 \cdot I) \cdot R_L = I \cdot R_{\text{RTD}} + 3 \cdot I \cdot R_L$$

$$V_{\text{meas}_-} = I \cdot R_L + (2 \cdot I) \cdot R_L = 3 \cdot I \cdot R_L$$

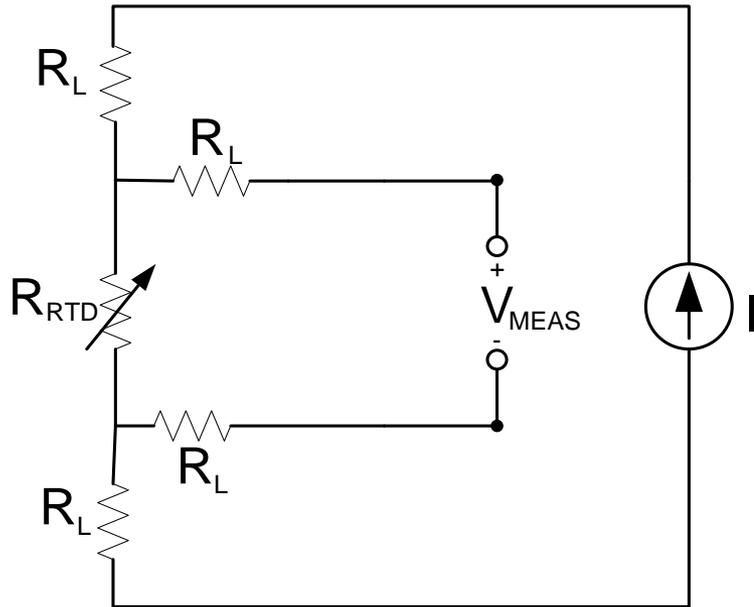
$$V_{\text{meas}_+} - V_{\text{meas}_-} = (I \cdot R_{\text{RTD}} + 3 \cdot I \cdot R_L) - (3 \cdot I \cdot R_L) = I \cdot R_{\text{RTD}}$$

$$V_{\text{meas}} = V_{\text{source}} \left[\left(\frac{R_{\text{RTD}} + R_L}{R_A + R_{\text{RTD}} + 2 \cdot R_L} \right) - \frac{1}{2} \right]$$

$$\text{Error} = V_{\text{source}} \cdot \left[\frac{R_L \cdot (R_A - R_{\text{RTD}})}{(R_A + R_{\text{RTD}}) \cdot (R_A + 2 \cdot R_L + R_{\text{RTD}})} \right]$$

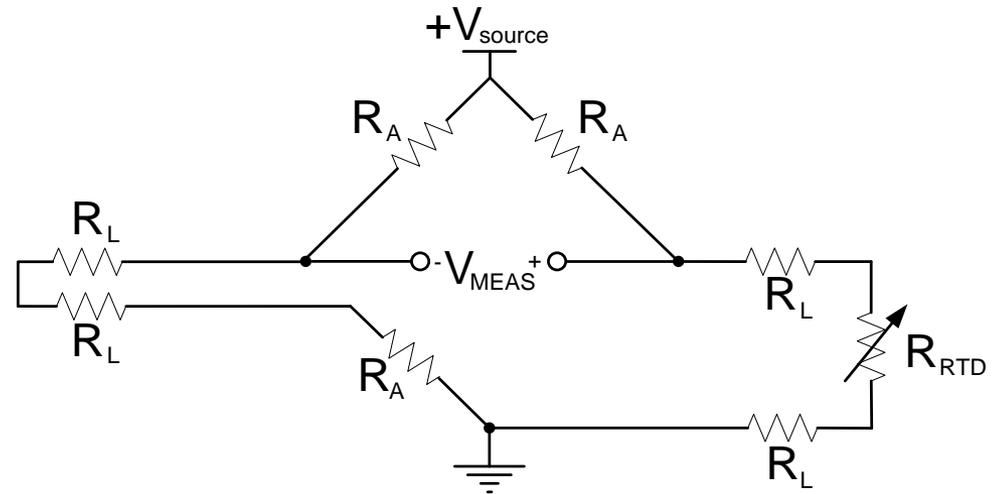
Error = 0 as long as I_{source1} = I_{source2} and R_L are equal

4-Wire Measurements



$$V_{\text{meas}} = I_{\text{source}} \cdot R_{\text{RTD}}$$

System Errors reduced to measurement circuit accuracy

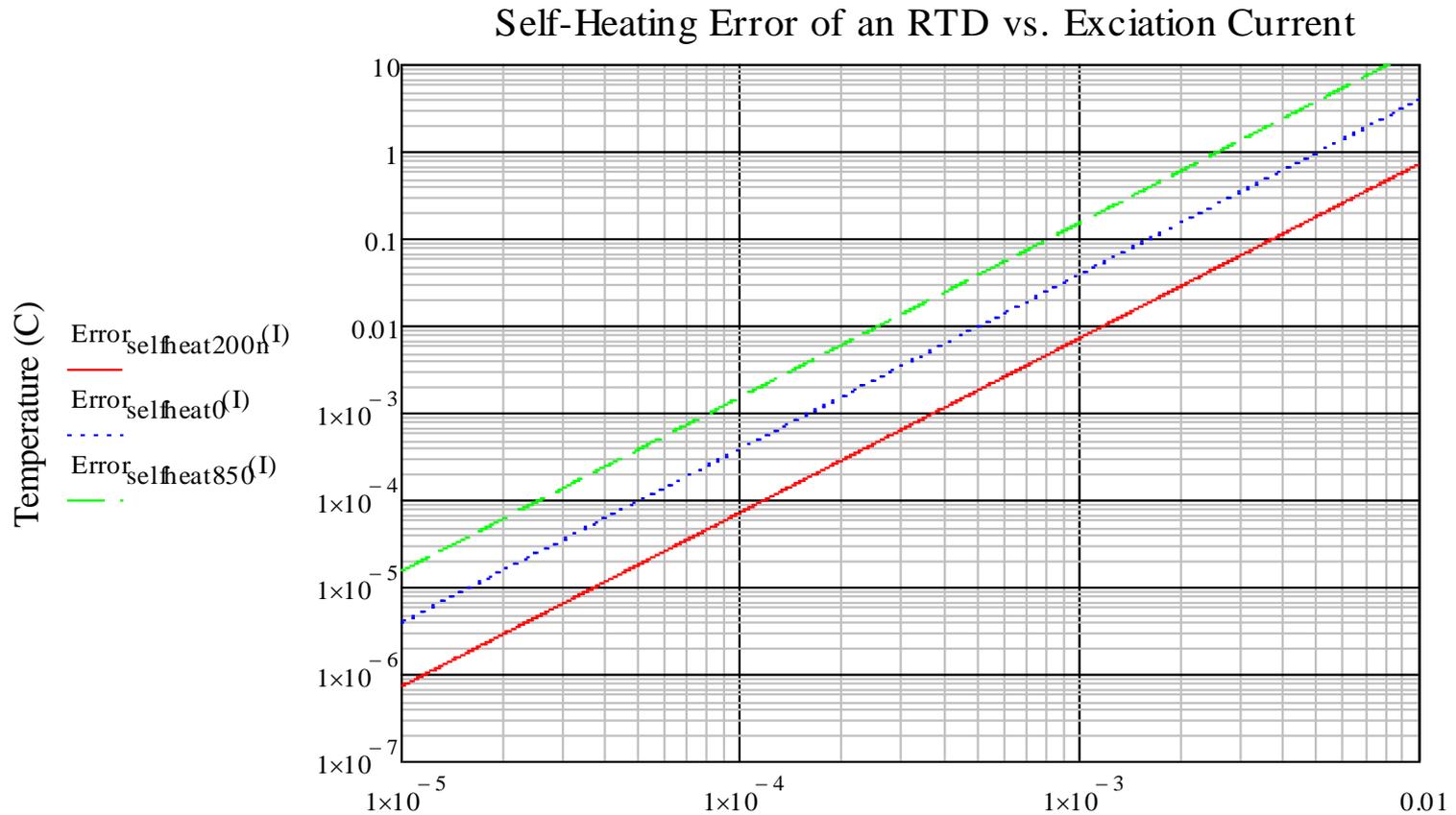


$$V_{\text{meas}} = \frac{R_A \cdot V_{\text{source}} \cdot (R_A - R_{\text{RTD}})}{2 \cdot R_A^2 + 6 \cdot R_A \cdot R_L + 2 \cdot R_{\text{RTD}} R_A + 4 \cdot R_L^2 + 2 \cdot R_{\text{RTD}} R_L}$$

$$\text{Error} = V_{\text{source}} \left[\frac{R_L \cdot (2.0 R_A - 2.0 R_{\text{RTD}})}{(R_A + R_{\text{RTD}}) \cdot (R_A + 4.0 R_L + R_{\text{RTD}})} \right]$$

Self-Heating Errors of RTD

- Typically 2.5mW/C – 60mW/C
- Set excitation level so self-heating error is <10% of the total error budget



RTD Resistance vs Temperature

Callendar-Van Dusen Equations

$$\text{For } (T > 0): \text{RTD}(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot (T^2) \right]$$

$$\text{For } (T < 0): \text{RTD}(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot (T^2) + C \cdot (T^3) \cdot (T - 100) \right]$$

Equation Constants for

IEC 60751 PT-100 RTD ($\alpha = 0.00385$)

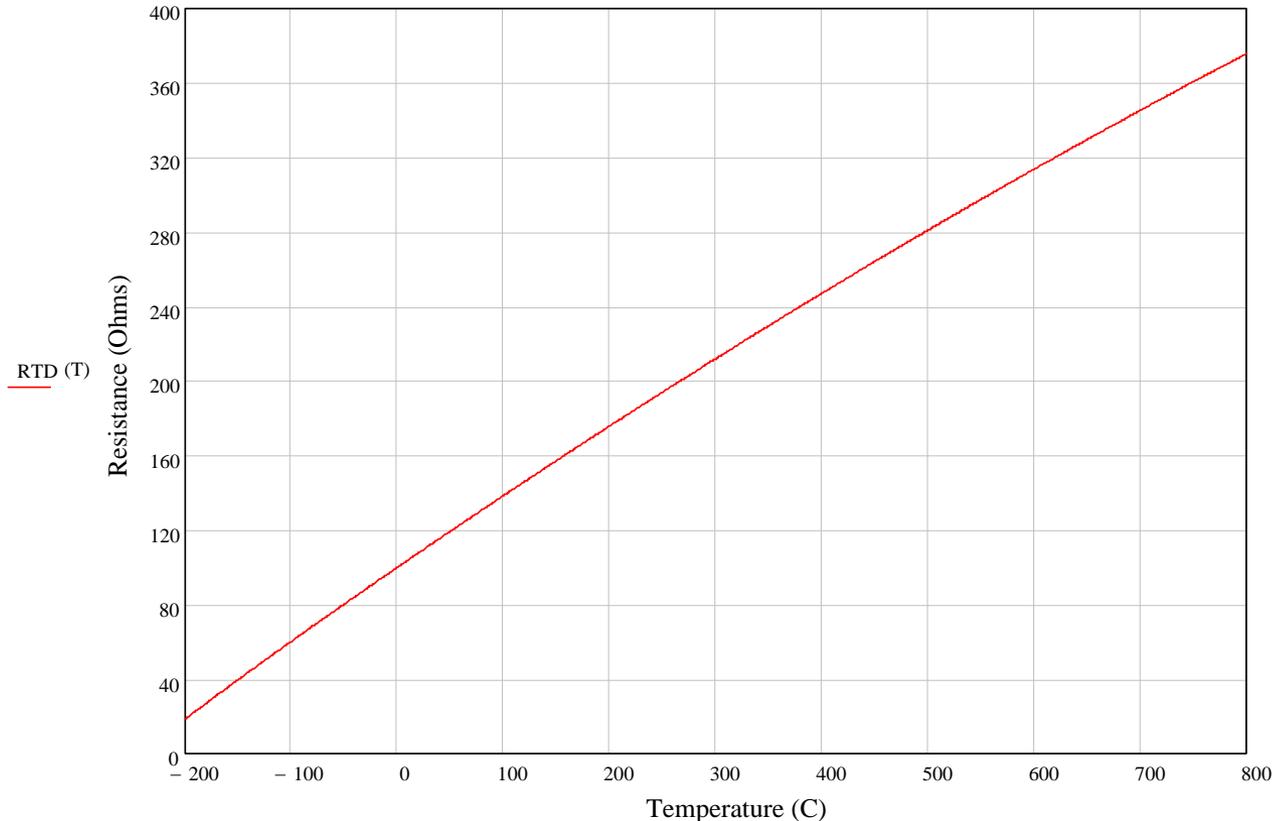
$$R_0 := 100$$

$$A := 3.908310^{-3}$$

$$B := -5.77510^{-7}$$

$$C := -4.18310^{-12}$$

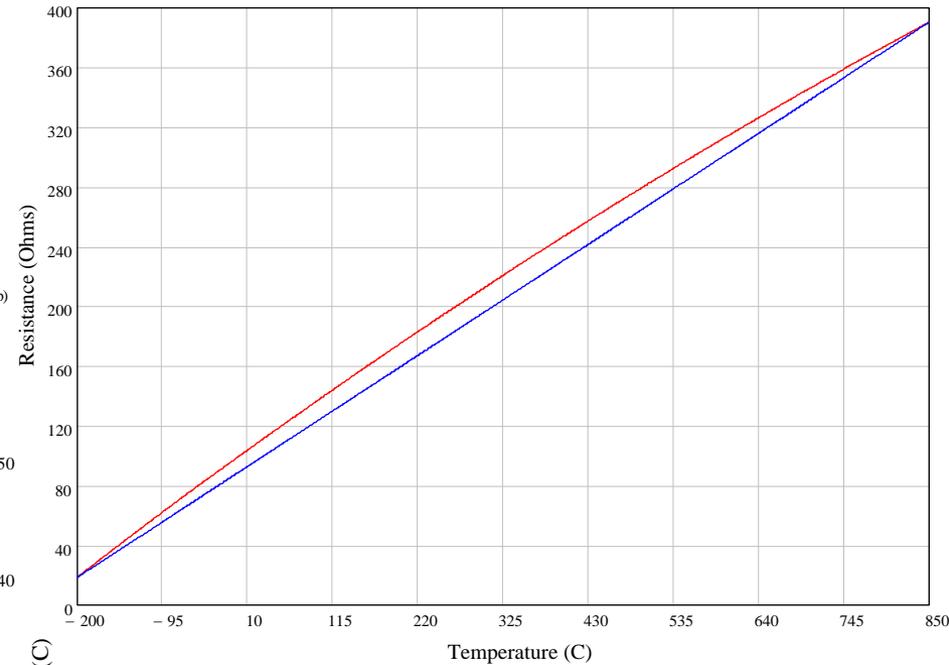
RTD Resistance vs. Temperature



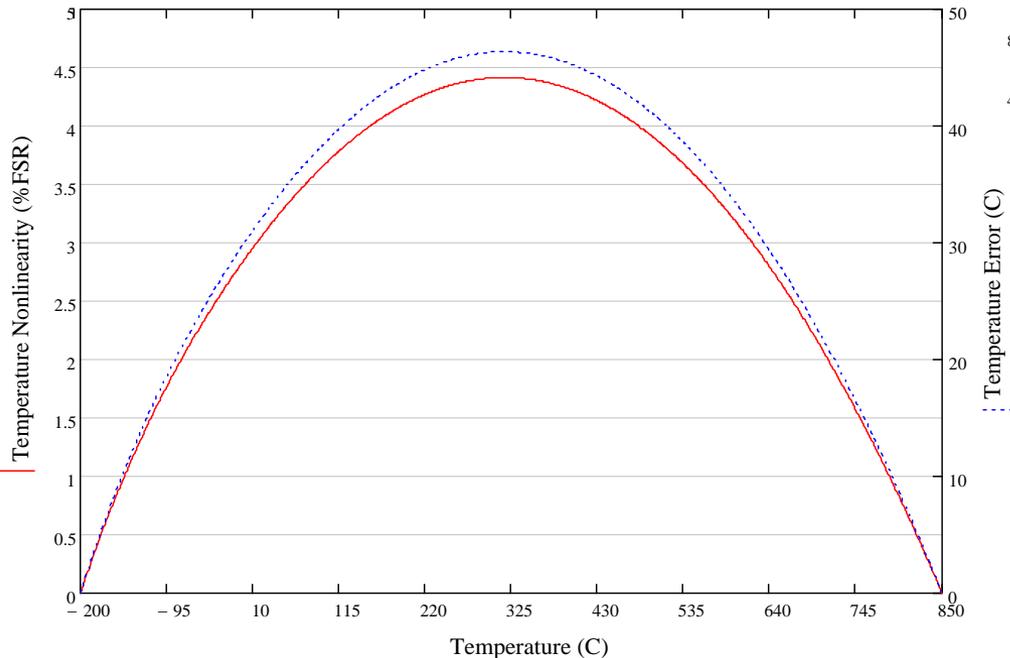
RTD Nonlinearity

Linear fit between the two end-points shows the Full-Scale nonlinearity

RTD Resistance vs. Temperature



Nonlinearity and Temperature Error vs. Temperature



Nonlinearity = 4.5%

Temperature Error > 45C

RTD Nonlinearity

$$\text{For } (T > 0): \text{RTD}(T) := R_0 \cdot [1 + A \cdot T + B \cdot (T^2)]$$

$$\text{RTD}_{\text{linear}}(T) := R_0 \cdot (1 + A \cdot T)$$

$$\text{For } (T < 0): \text{RTD}(T) := R_0 \cdot [1 + A \cdot T + B \cdot (T^2) + C \cdot (T^3) \cdot (T - 100)]$$

$$R_0 := 100$$

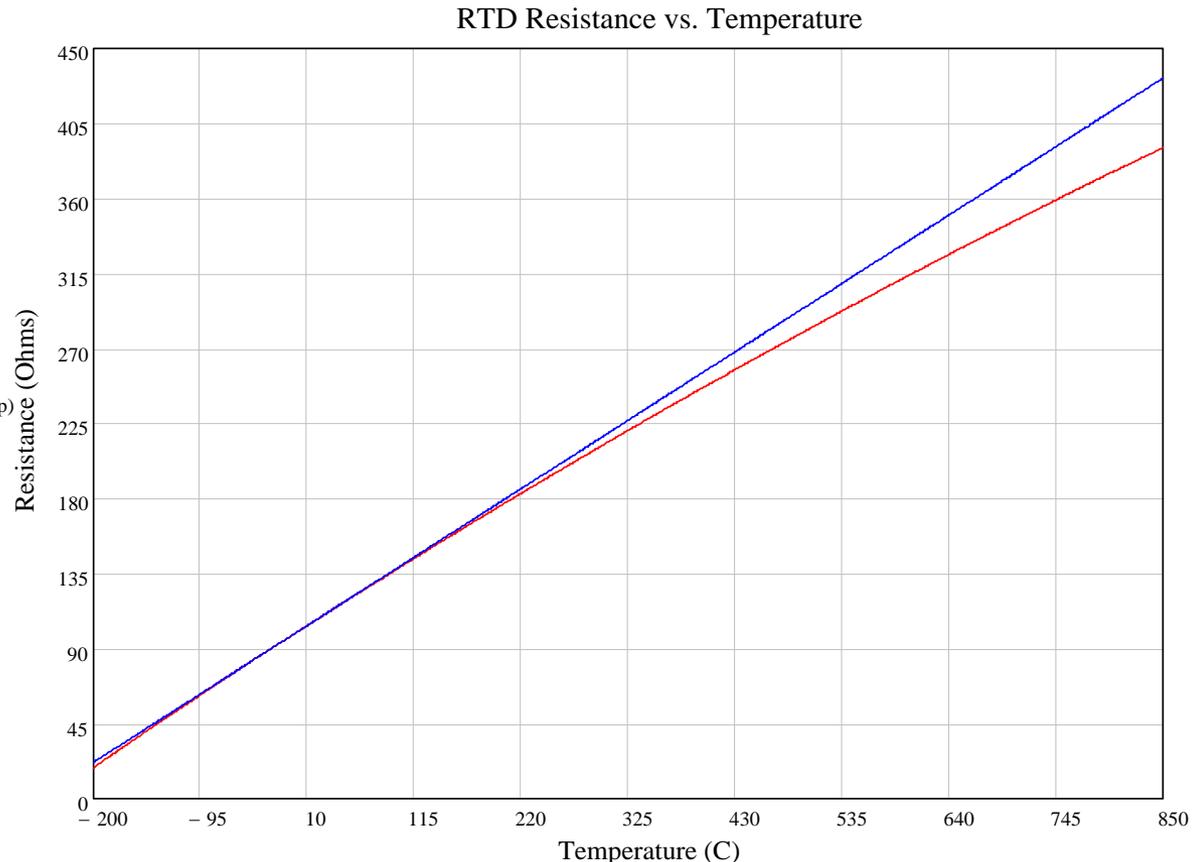
$$A := 3.908310^{-3}$$

$$B := -5.77510^{-7}$$

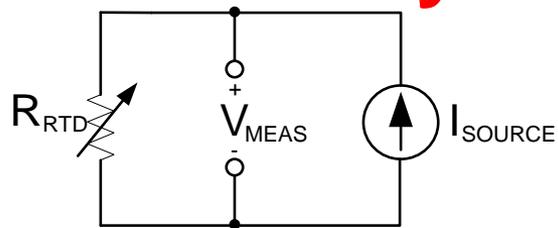
$$C := -4.18310^{-12}$$

B and C terms are negative so 2nd and 3rd order effects decrease the sensor output over the sensor span.

RTD(Temp)
RTD_{linear}(Temp)

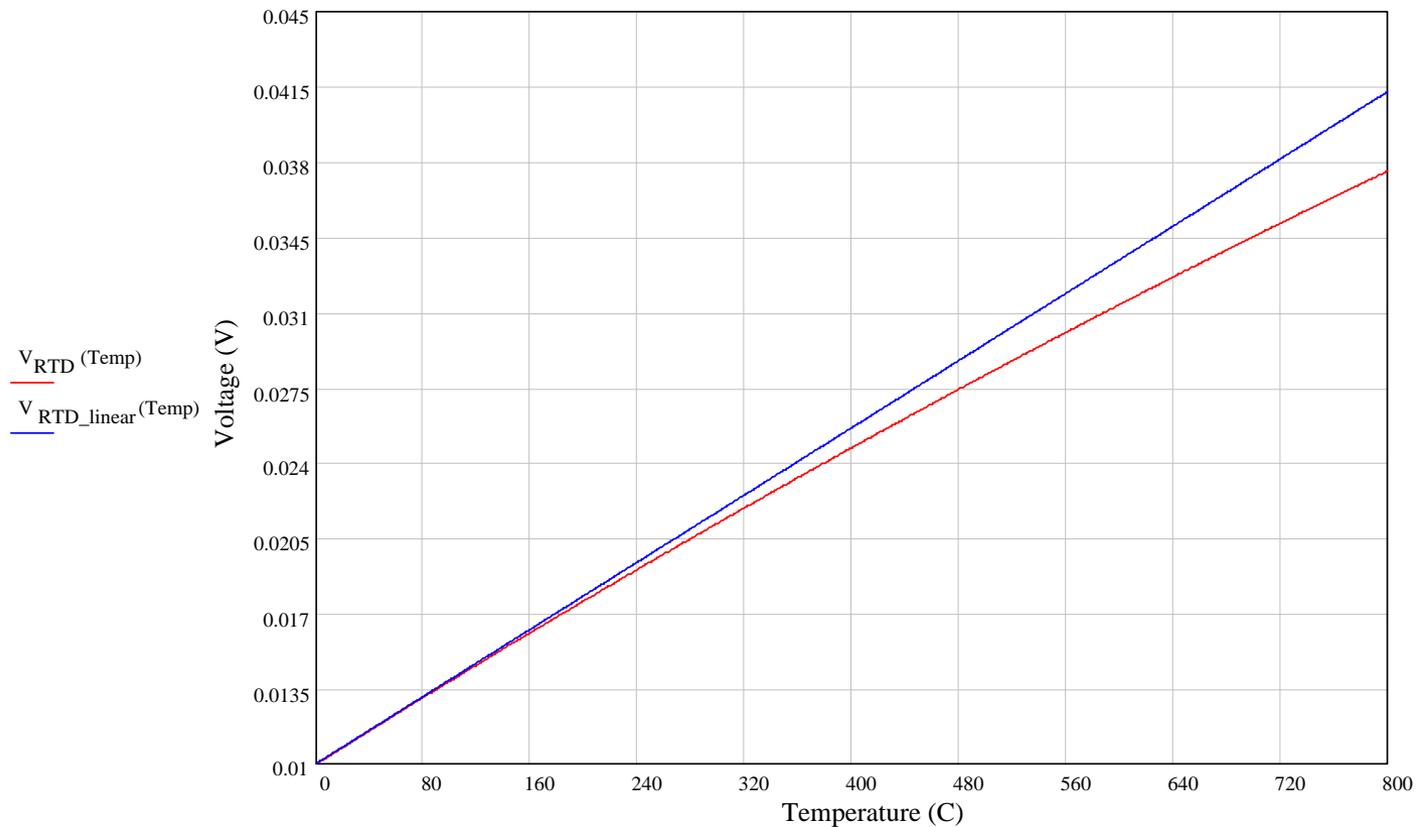


Measurement Nonlinearity



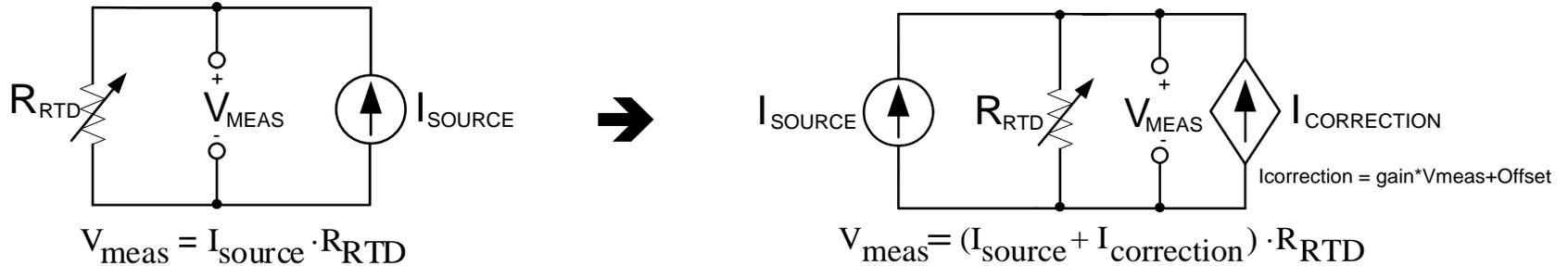
$$V_{meas} = I_{source} \cdot R_{RTD}$$

RTD Sensor Output vs. Temperature (I_{source} = 100uA)

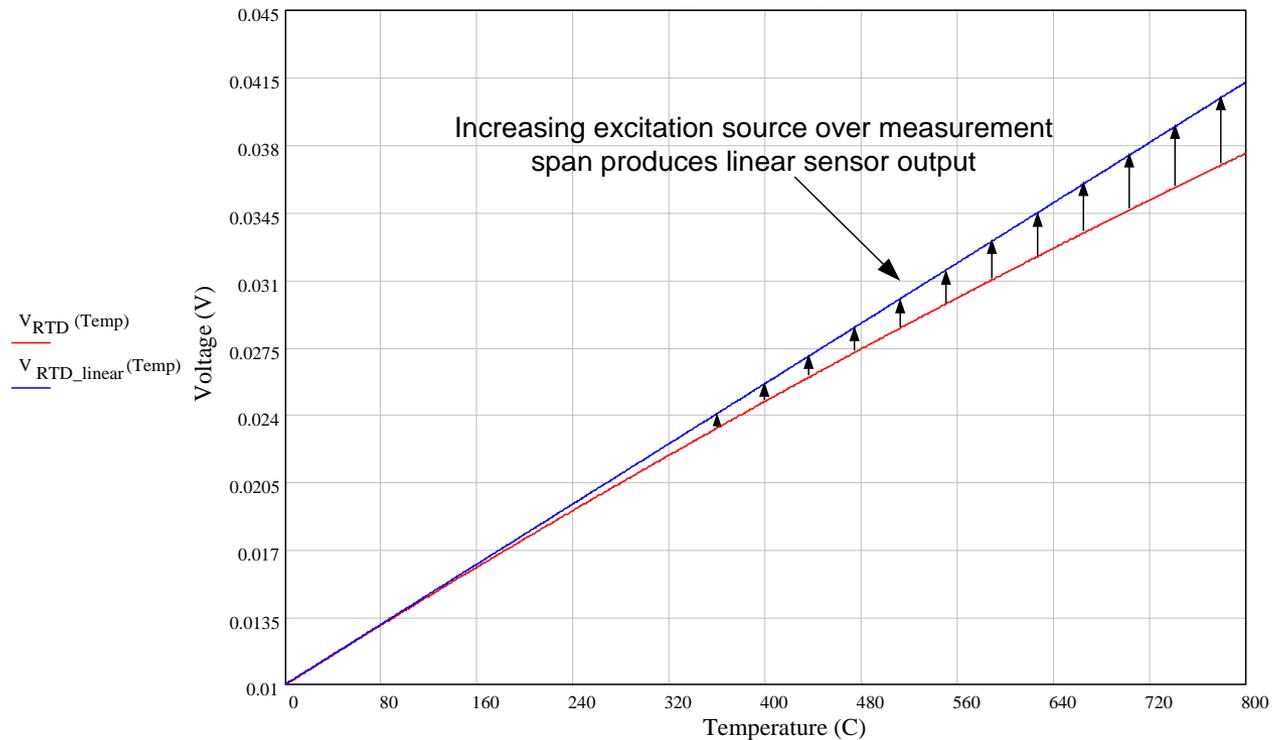


Correcting for Non-Linearity

Sensor output decreases over span? Compensate by increasing excitation over span!



RTD Sensor Output vs. Temperature ($I_{source} = 100\mu A$)



Correcting for Non-linearity

$$I_{\text{source}} := 0.0005$$

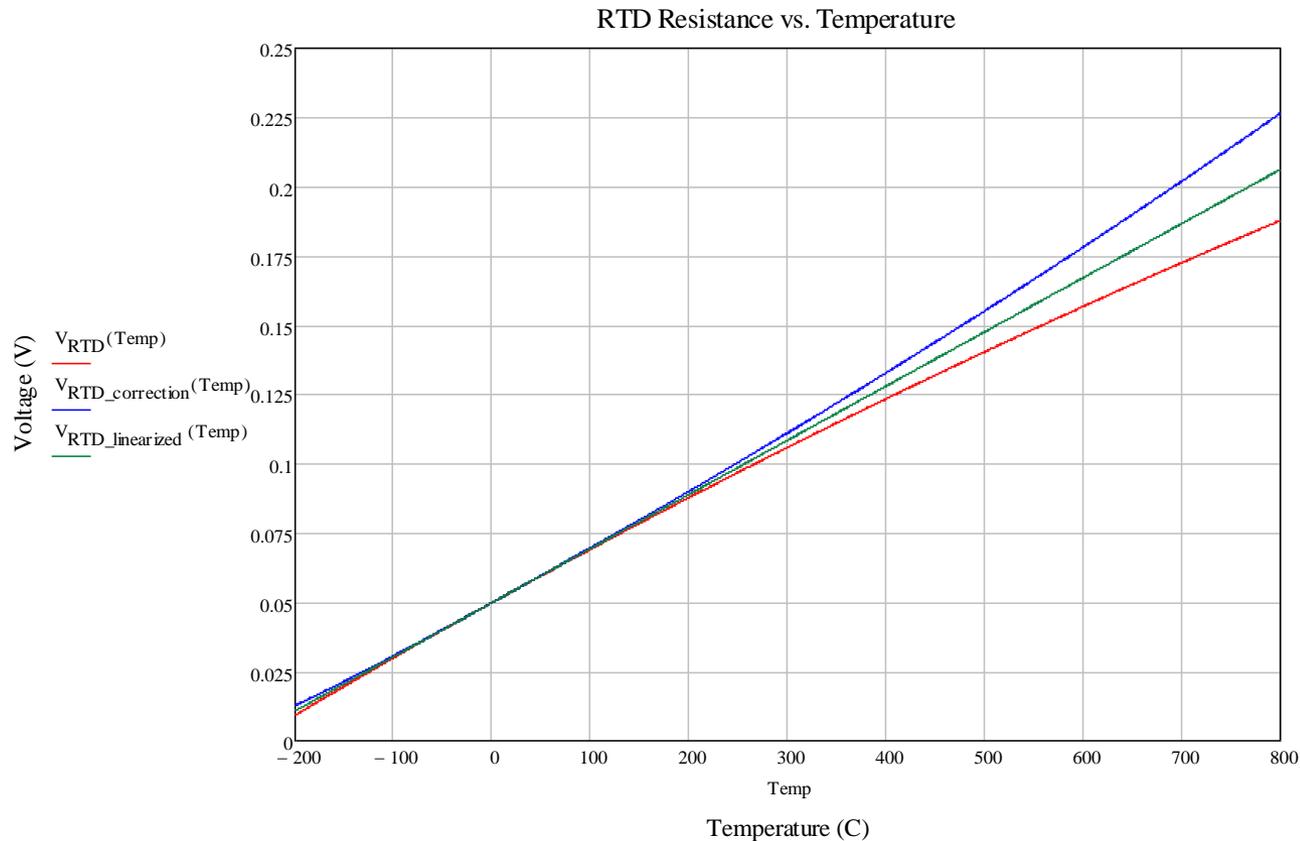
$$V_{\text{RTD}}(T) := \text{RTD}(T) \cdot I_{\text{source}}$$

$$V_{\text{RTD_linear}}(T) := \text{RTD}_{\text{linear}}(T) \cdot I_{\text{source}}$$

$$I_{\text{source_correction}}(T) := I_{\text{source}} + \frac{(V_{\text{RTD_linear}}(T) - V_{\text{RTD}}(T))}{\text{RTD}(T)}$$

$$V_{\text{RTD_correction}}(T) := \text{RTD}_{\text{linear}}(T) \cdot I_{\text{source_correction}}(T)$$

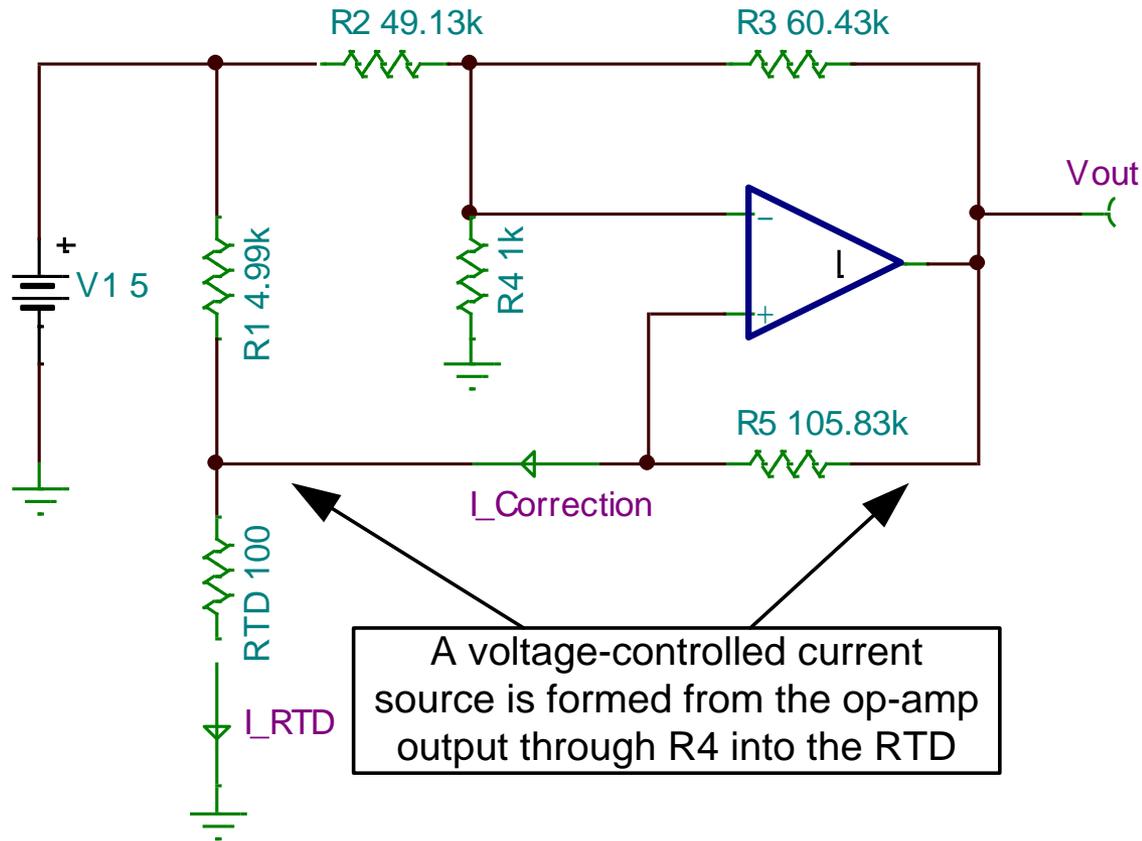
$$V_{\text{RTD_linearized}}(T) := I_{\text{source_correction}}(T) \cdot \text{RTD}(T)$$



Analog Linearization Circuits

Analog Linearization Circuits

Two-Wire Single Op-Amp



Example
Amplifiers:

Low-Voltage:

OPA333
OPA376

High Voltage:

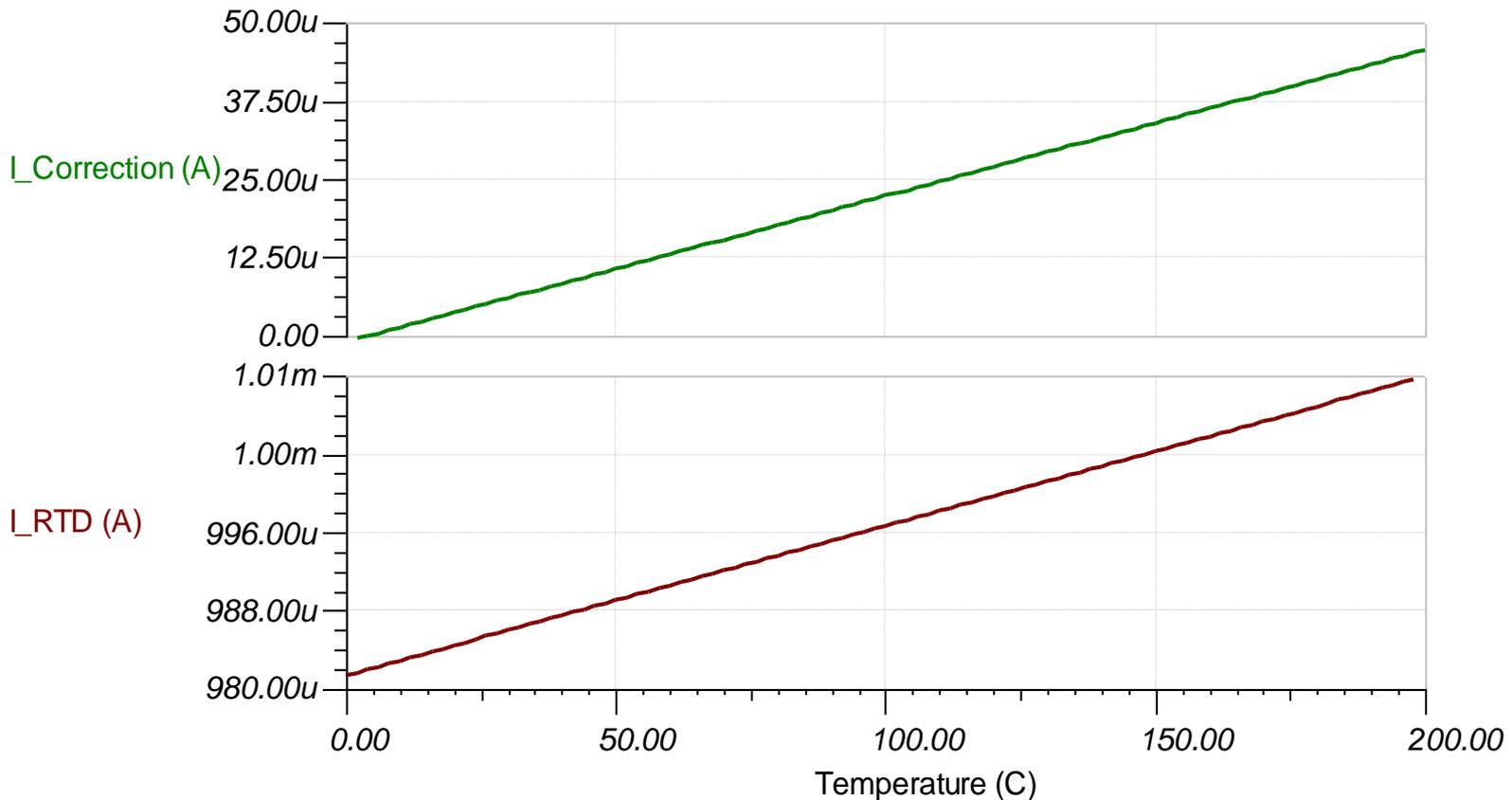
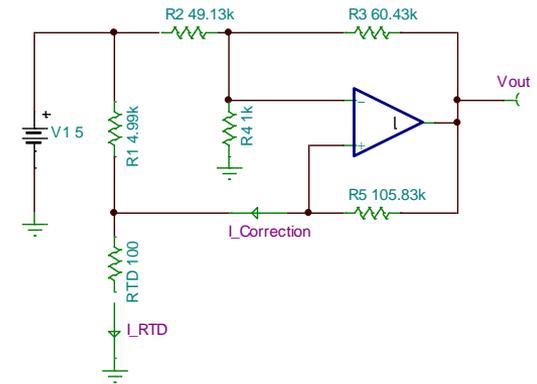
OPA188
OPA277

This circuit is designed for a 0-5V output for a 0-200C temperature span. Components R2, R3, R4, and R5 are adjusted to change the desired measurement temperature span and output.

Analog Linearization Circuits

Two-Wire Single Op-Amp

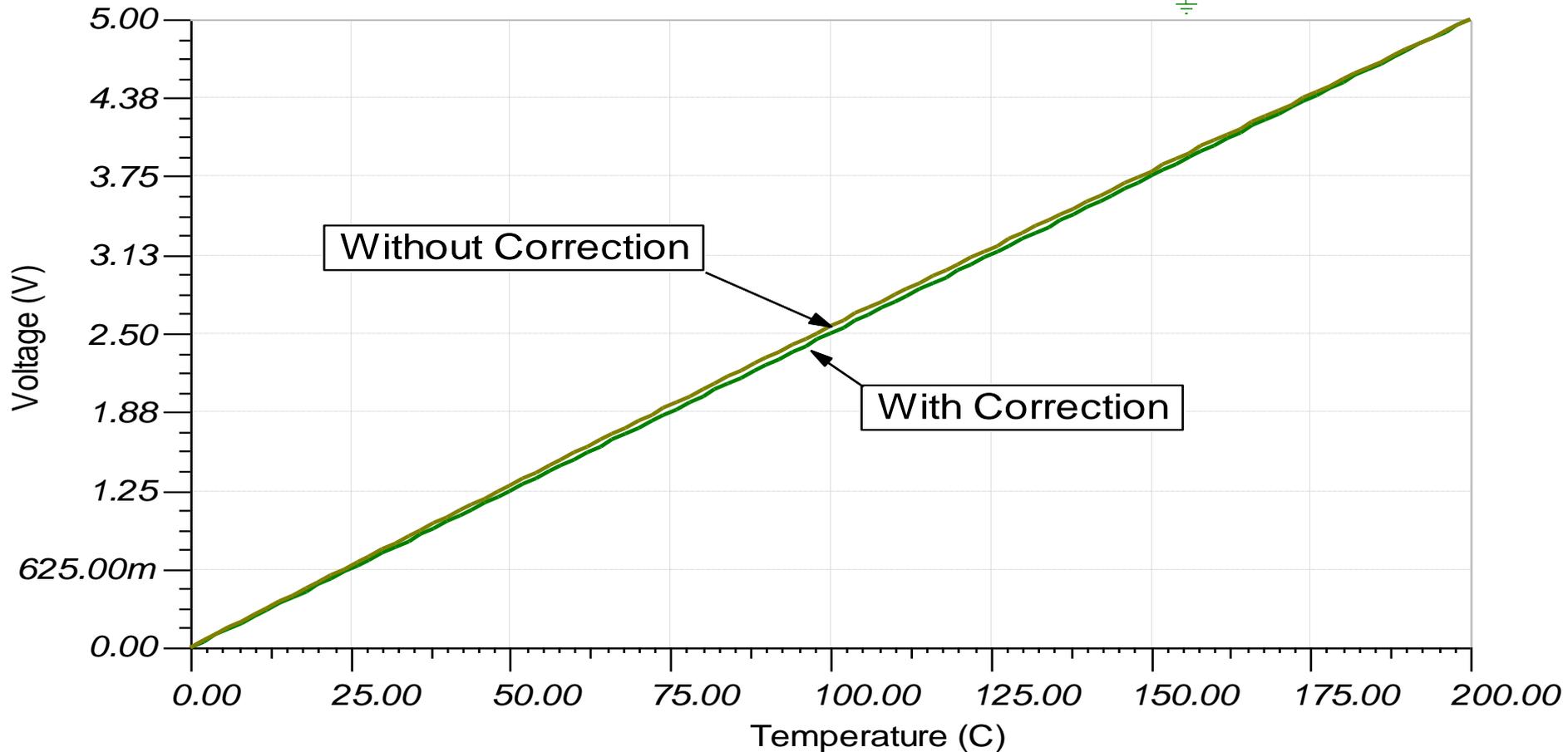
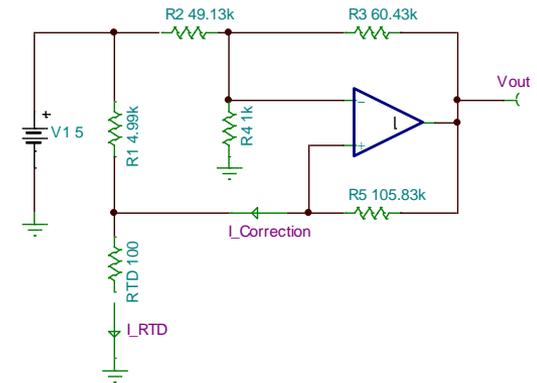
Non-linear increase in excitation current over temperature span will help correct non-linearity of RTD measurement



Analog Linearization Circuits

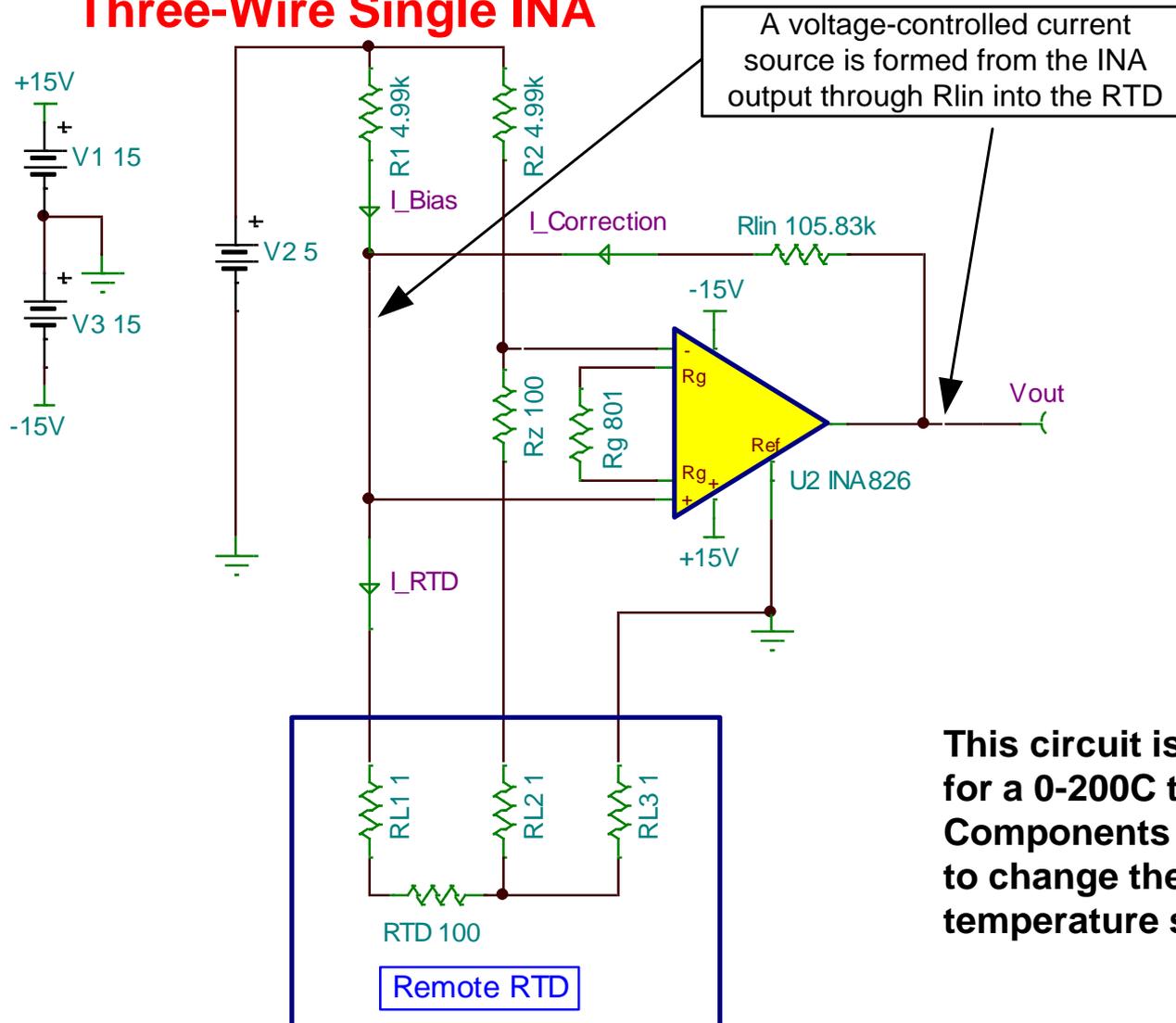
Two-Wire Single Op-Amp

This type of linearization typically provides a 20X - 40X improvement in linearity



Analog Linearization Circuits

Three-Wire Single INA



Example Amplifiers:

Low-Voltage:

INA333

INA114

High Voltage

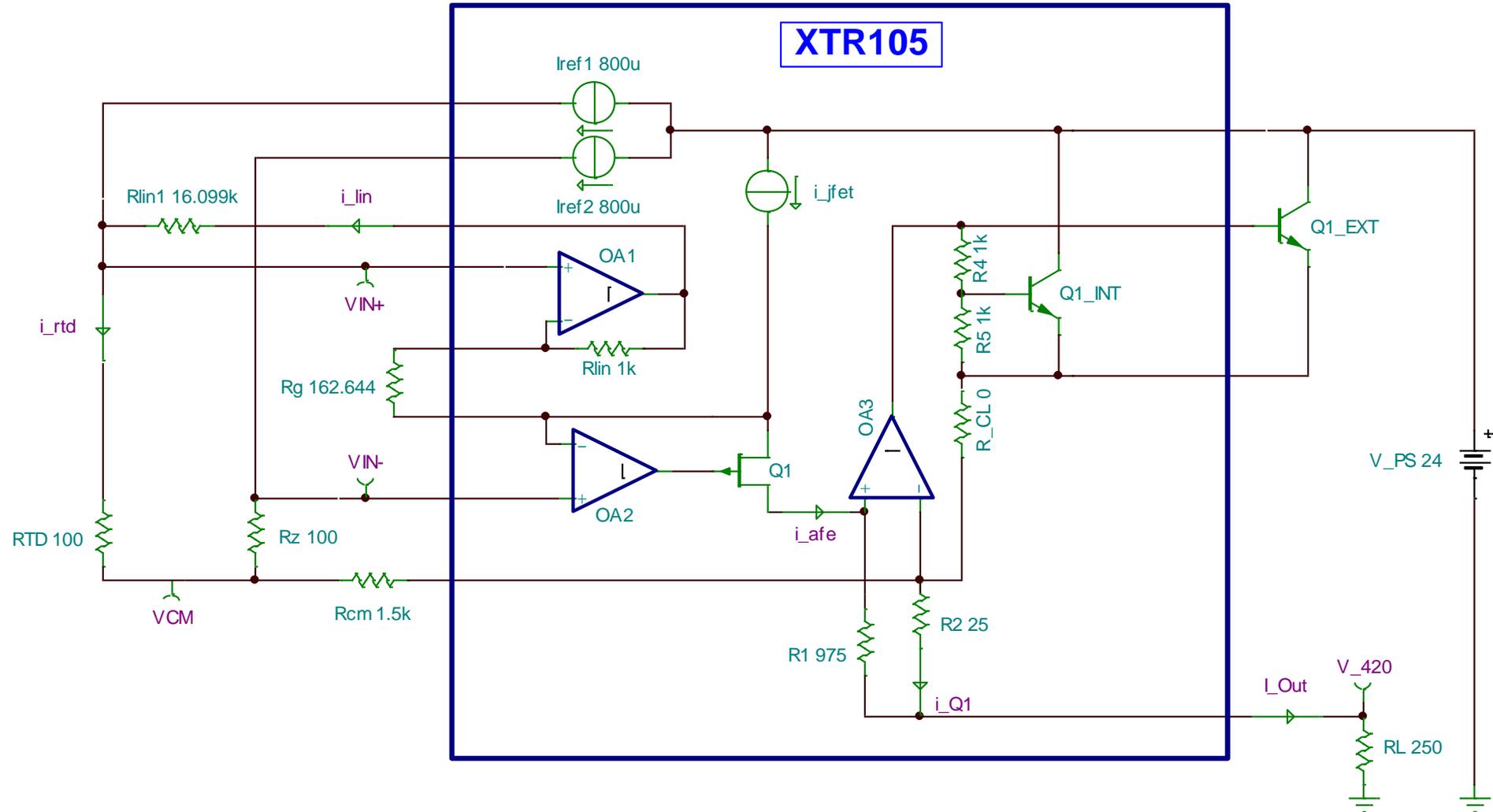
INA826

INA114

This circuit is designed for a 0-5V output for a 0-200C temperature span. Components R_z, R_g, and R_{lin} are adjusted to change the desired measurement temperature span and output.

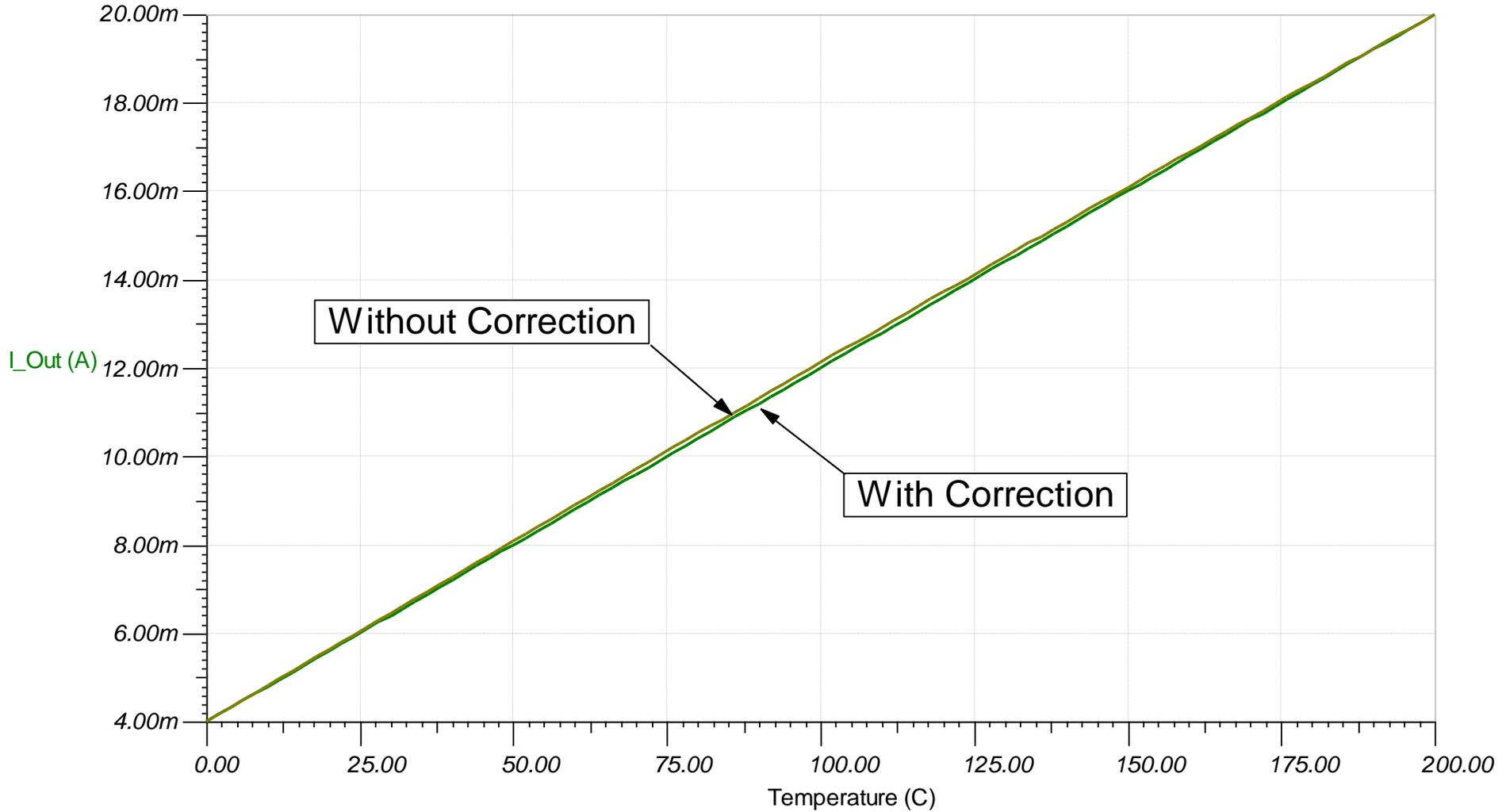
Analog Linearization Circuits

XTR105 4-20mA Current Loop Output



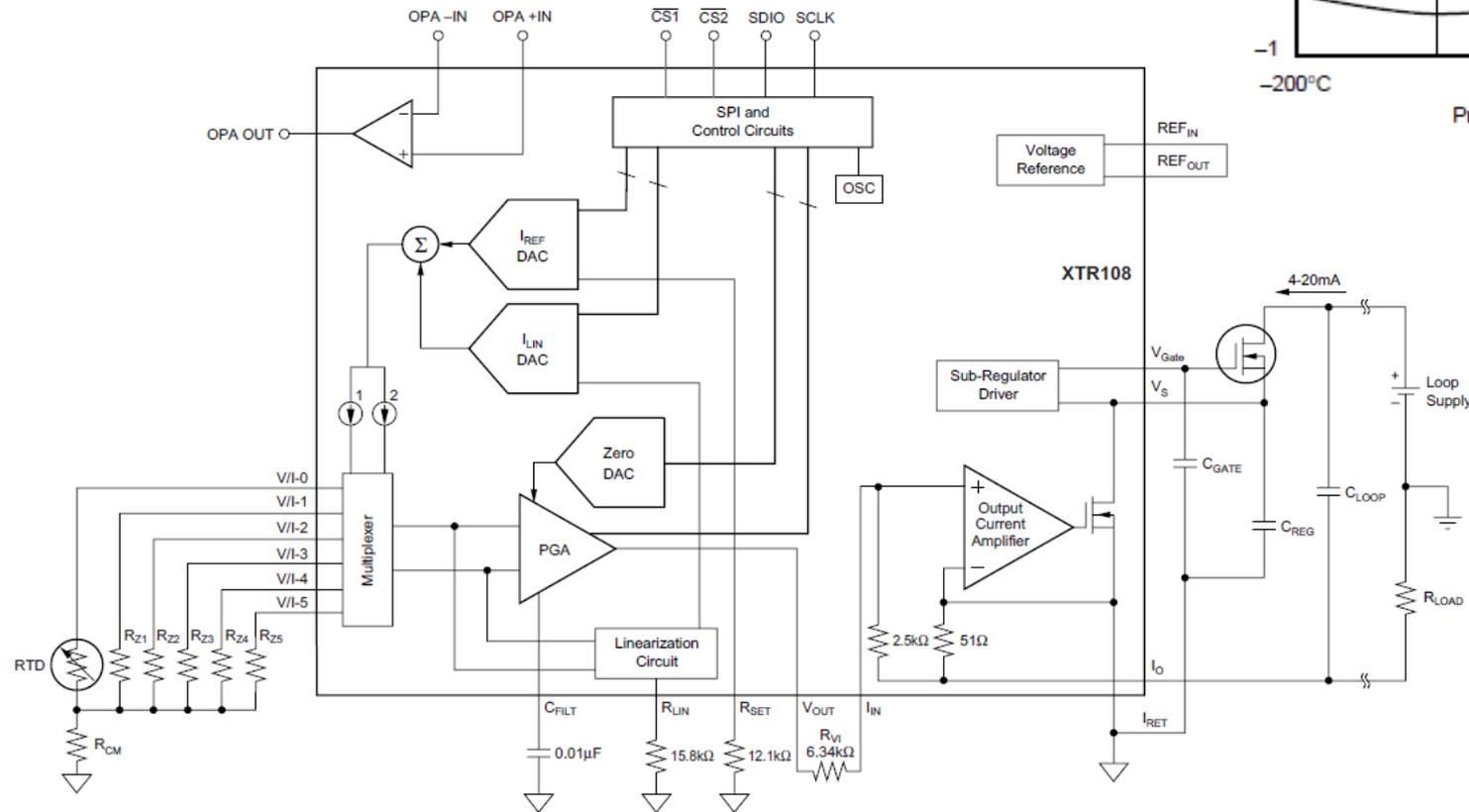
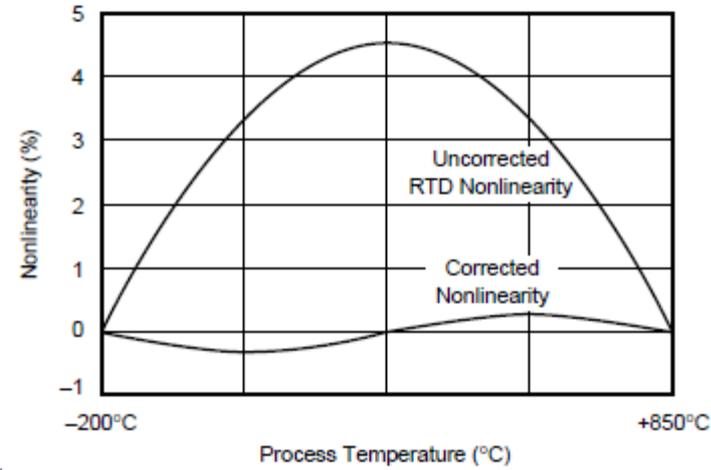
Analog Linearization Circuits

XTR105 4-20mA Current Loop Output



Analog + Digital Linearization Circuits

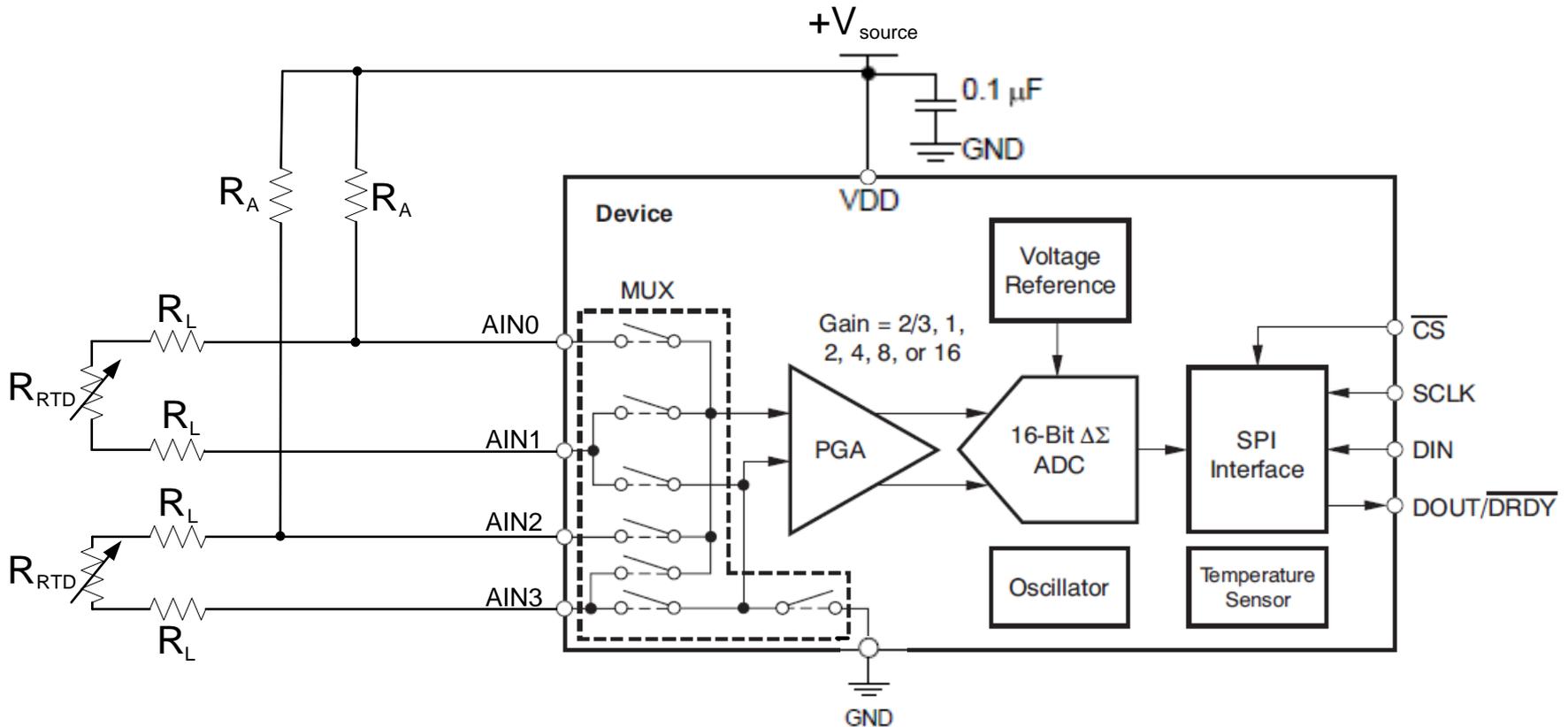
XTR108 4-20mA Current Loop Output



Digital Acquisition Circuits and Linearization Methods

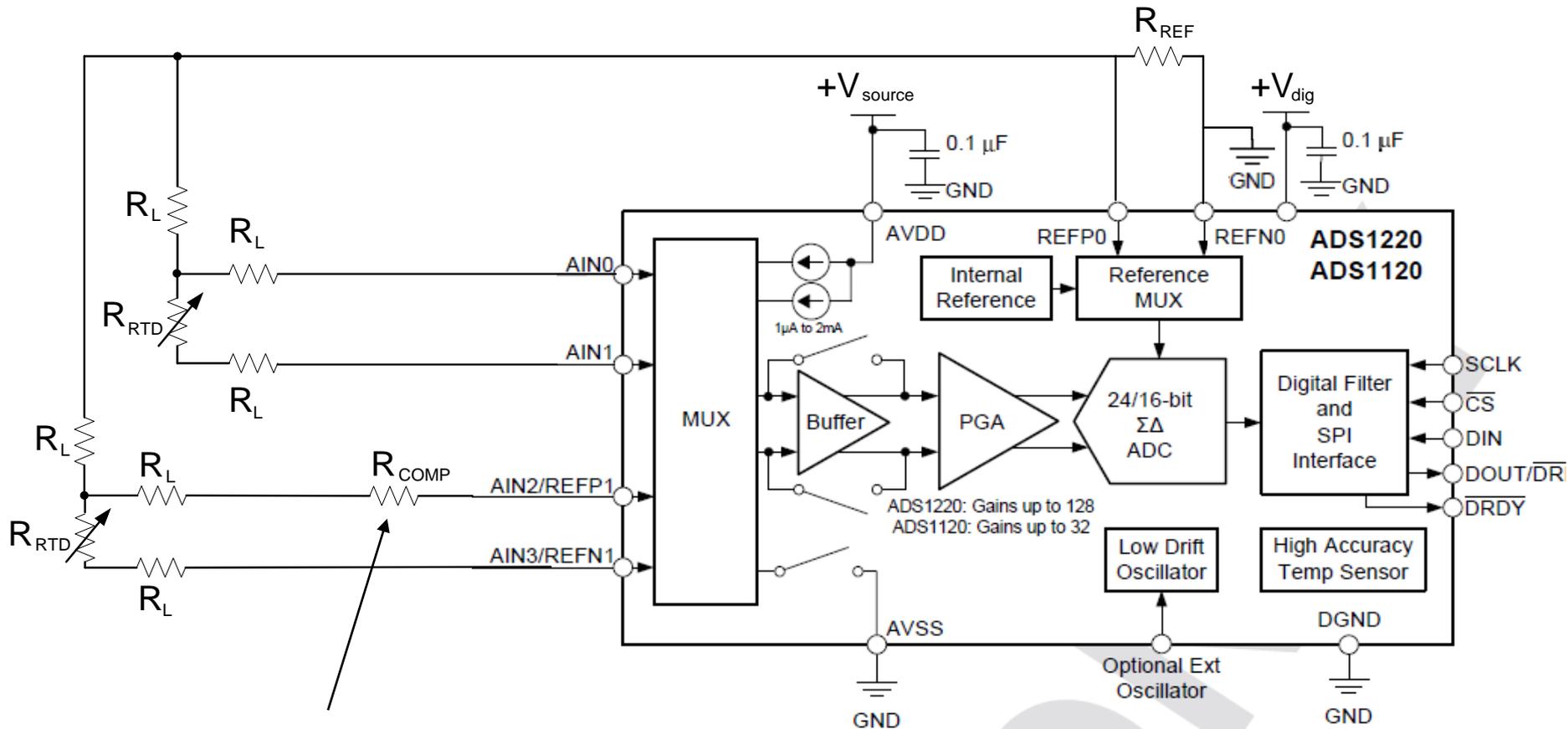
Digital Acquisition Circuits

ADS1118 16-bit Delta-Sigma 2-Wire Measurement with Half-Bridge



Digital Acquisition Circuits

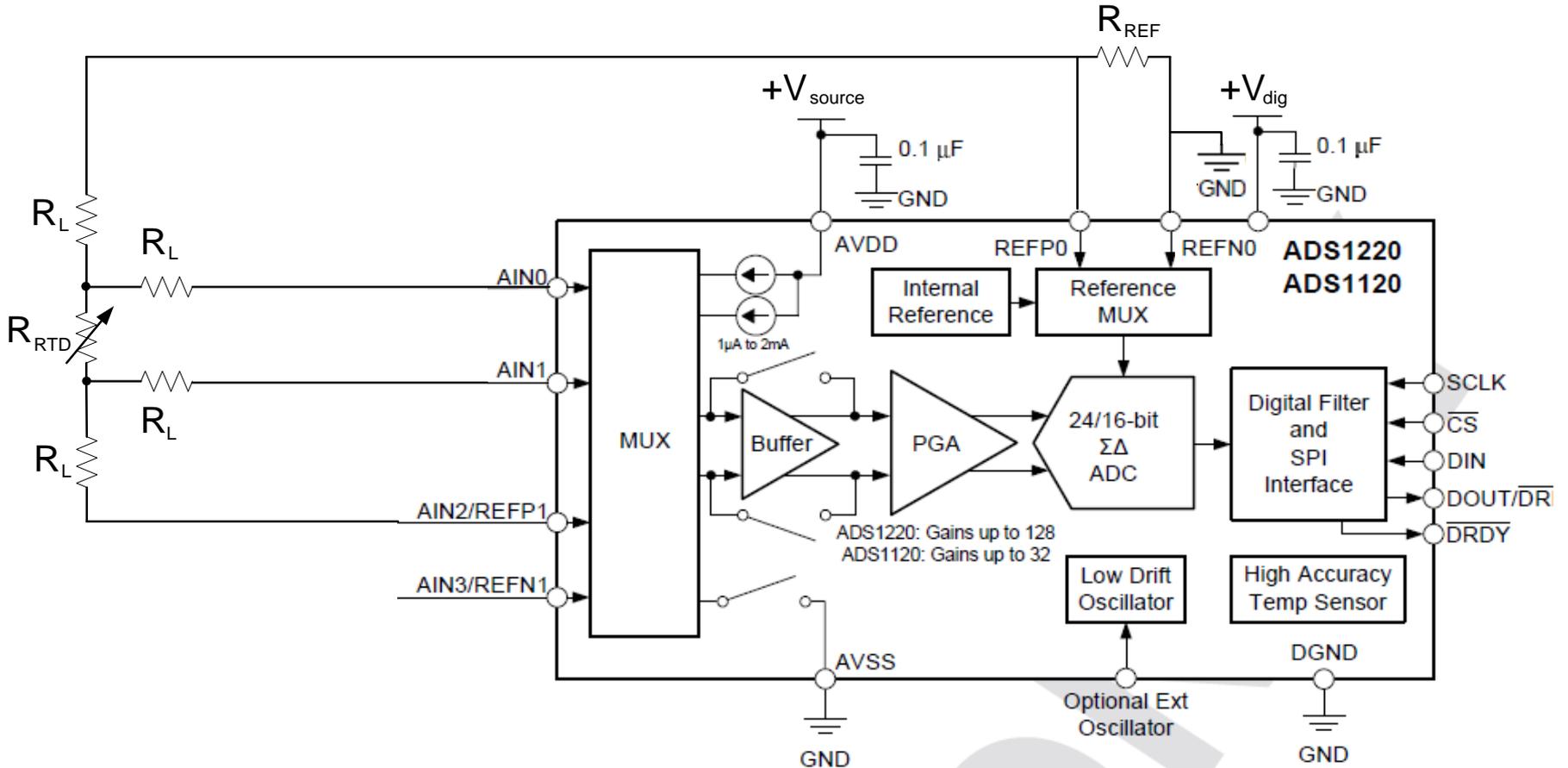
ADS1220 24-bit Delta-Sigma Two 3-wire RTDs



3-wire + Rcomp shown for AIN2/AIN3

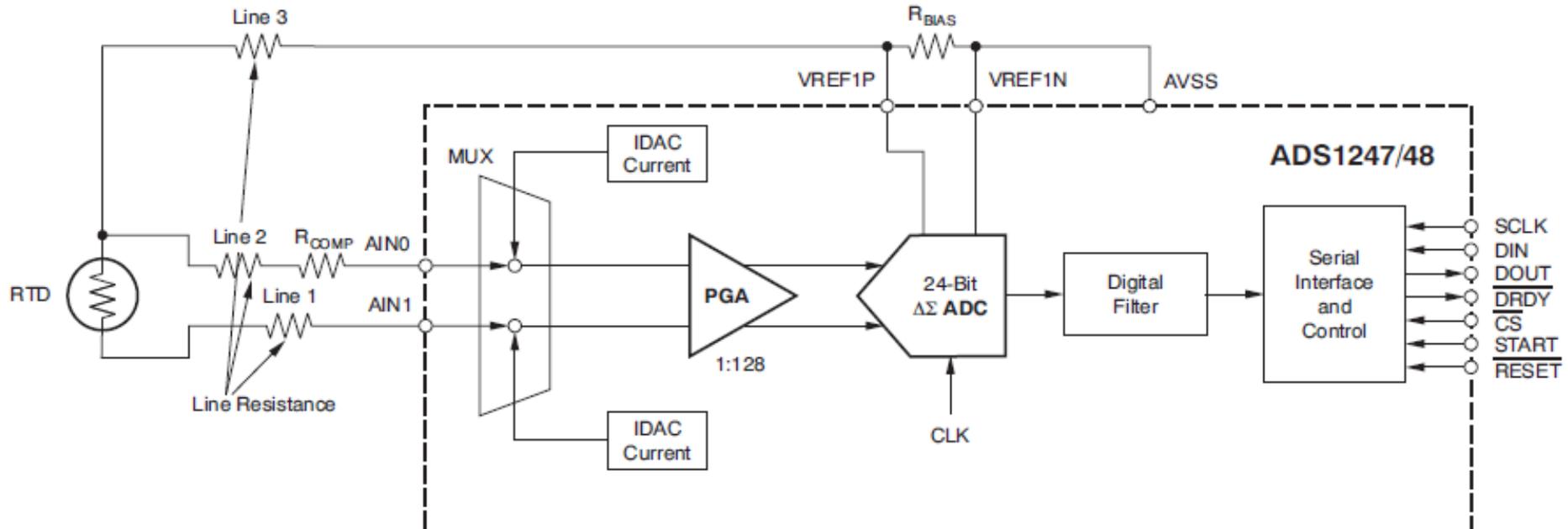
Digital Acquisition Circuits

ADS1220 24-bit Delta-Sigma One 4-Wire RTD



Digital Acquisition Circuits

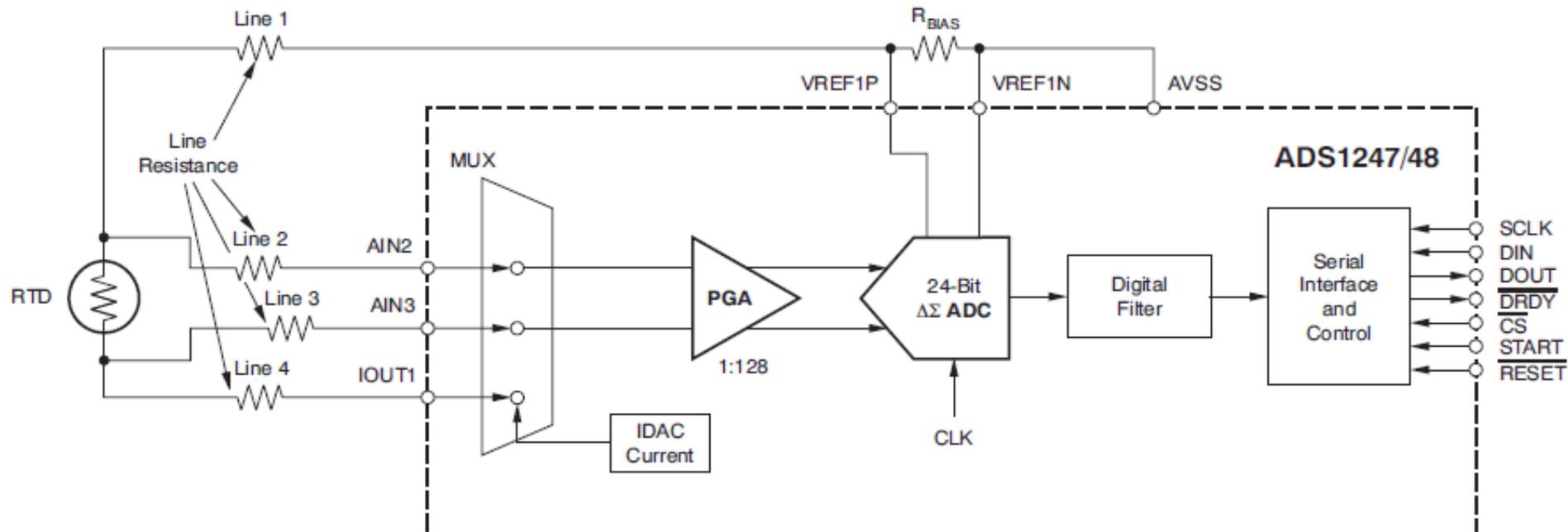
ADS1247 24-bit Delta-Sigma Three-Wire + Rcomp



Note: R_{BIAS} and R_{COMP} should be as close to the ADC as possible.

Digital Acquisition Circuits

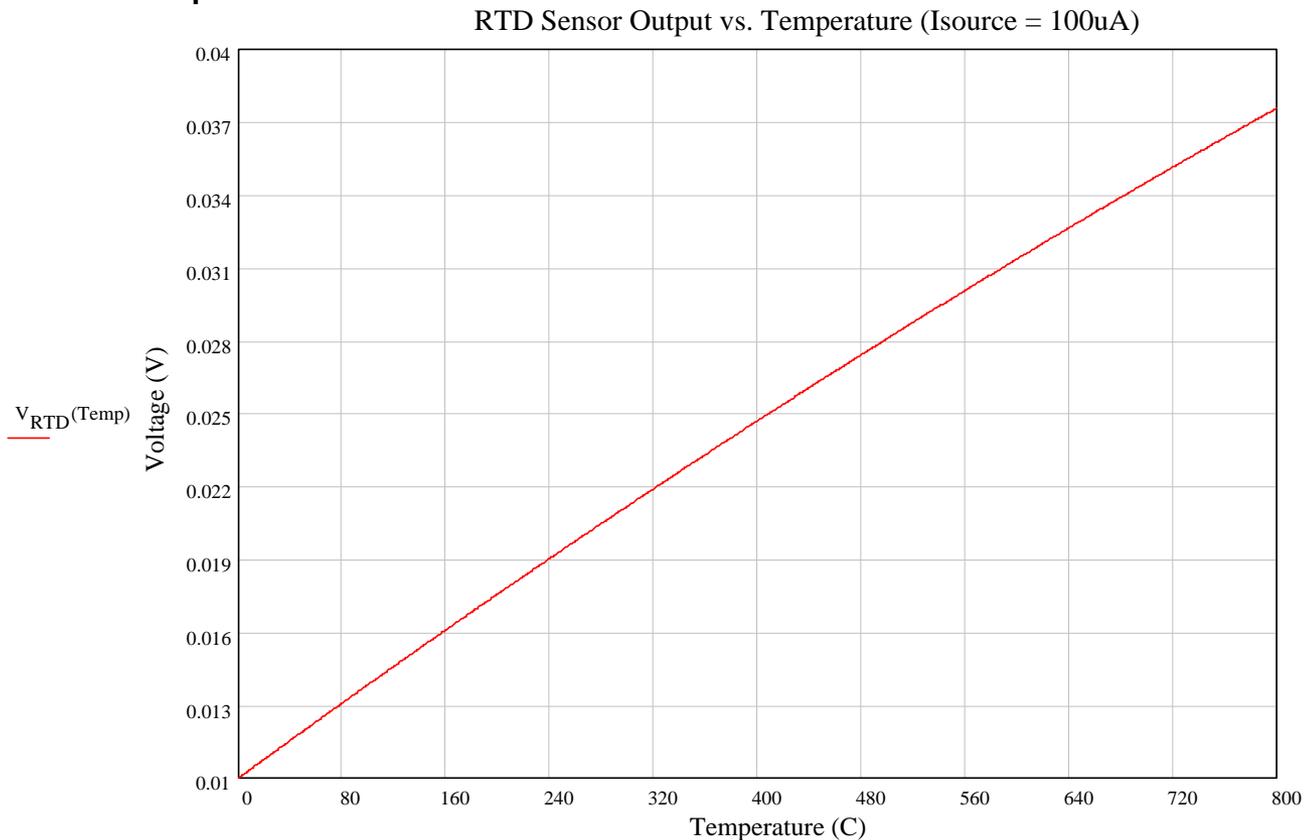
ADS1247 24-bit Delta-Sigma Four-Wire



Note: R_{BIAS} should be as close to the ADC as possible.

Digital Linearization Methods

- Three main options
 - Linear-Fit
 - Piece-wise Linear Approximations
 - Direct Computations



Digital Linearization Methods

Linear Fit

Pro's:

- Easiest to implement
- Very Fast Processing Time
- Fairly accurate over small temp span

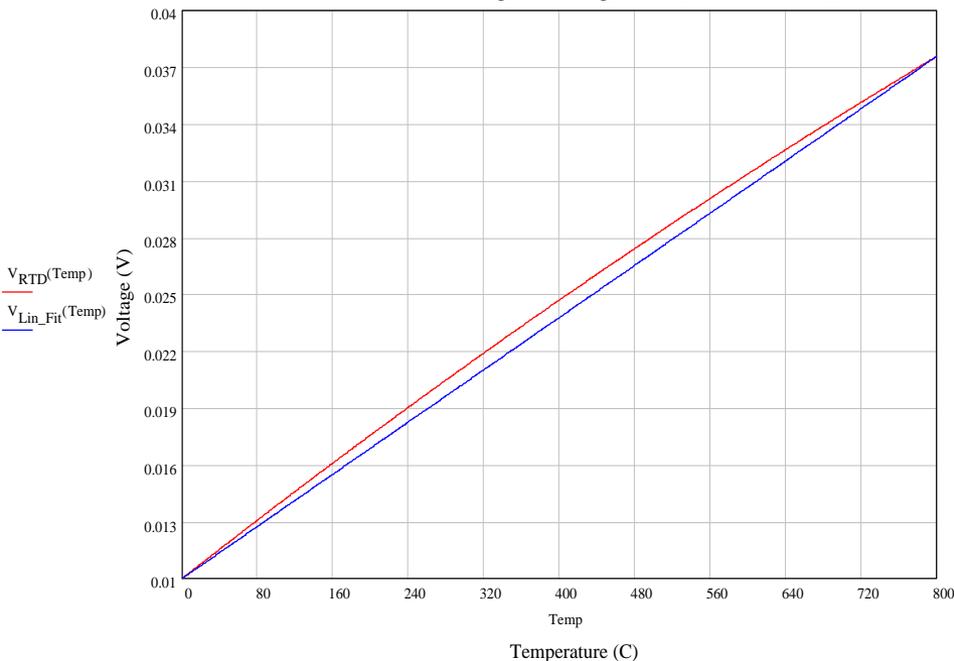
Con's:

Least Accurate

$$T_{\text{Linear}}(t) = A \cdot \text{RTD}(t) + B$$

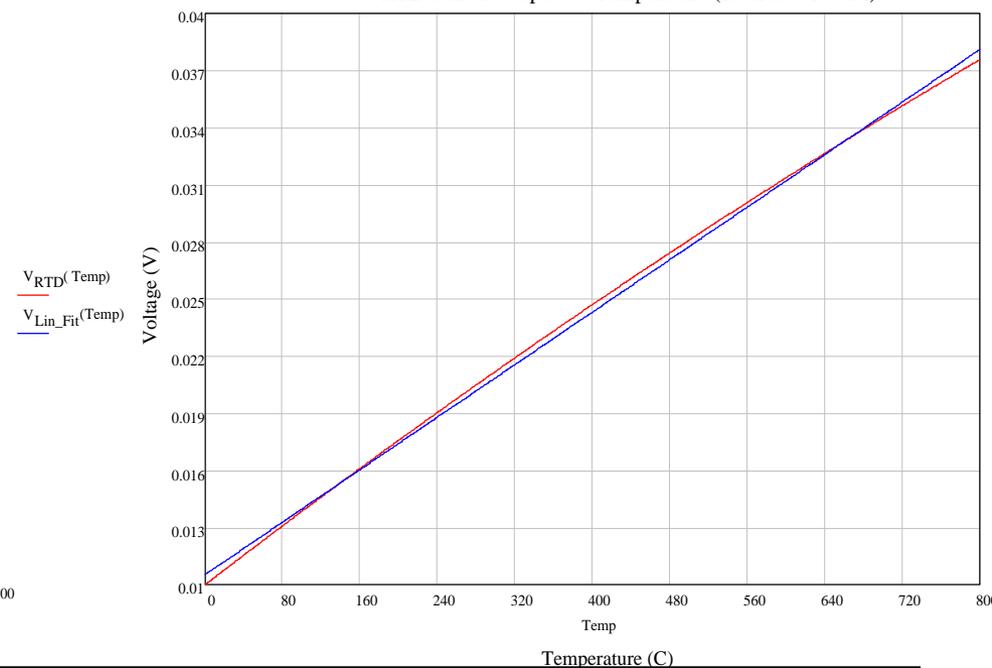
End-point Fit

RTD Sensor Output vs. Temperature (Isource = 100uA)



Best-Fit

RTD Sensor Output vs. Temperature (Isource = 100uA)



Digital Linearization Methods

Piece-wise Linear Fit

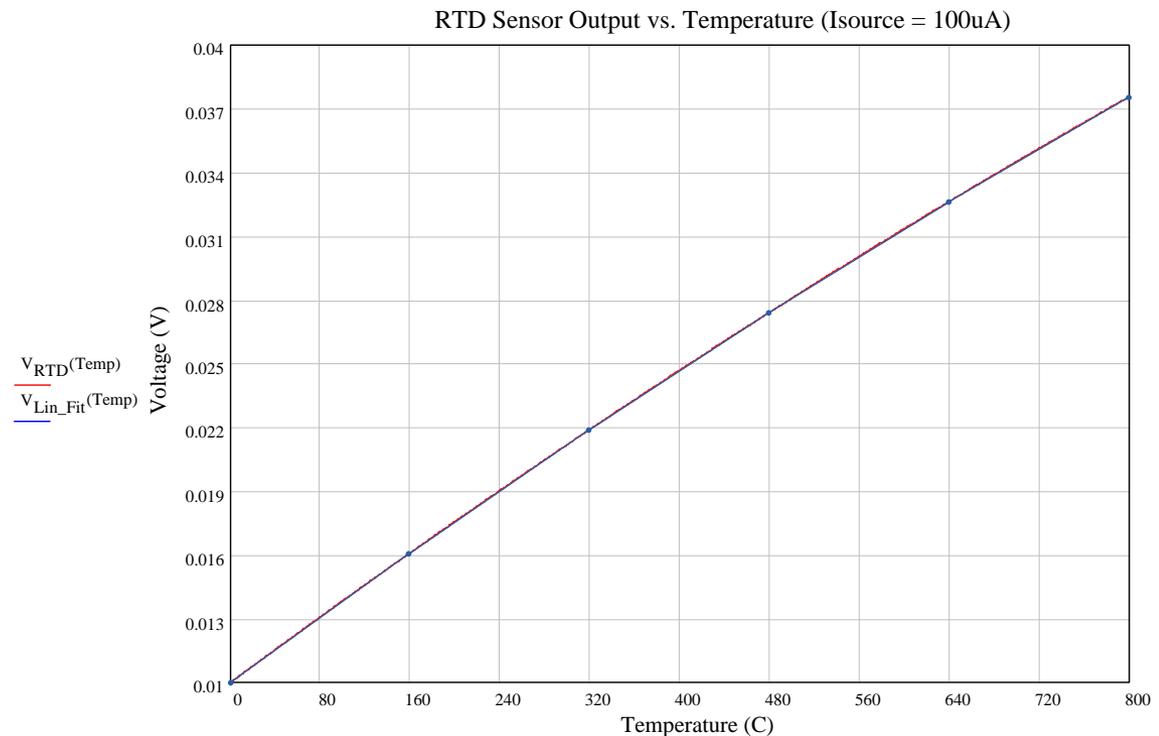
Pro's:

- Easy to implement
- Fast Processing Time
- Programmable accuracy

Con's:

- Code size required for coefficients

$$T_{\text{Peicewise}} = T(n - 1) + (T(n) - T(n - 1)) \left(\frac{RTD - RTD(n - 1)}{RTD(n) - RTD(n - 1)} \right)$$



Digital Linearization Methods

Direct Computation

Pro's:

- Almost Exact Answer, Least Error
- With 32-Bit Math Accuracy to +/-0.0001C

Con's:

- Processor intensive
- Requires Math Libraries
- Negative Calculation Requires simplification or bi-sectional solving

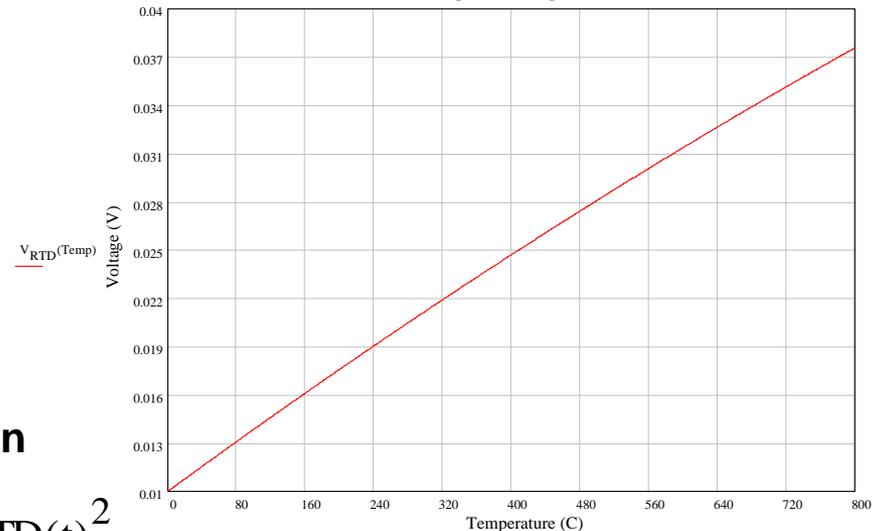
Positive Temperature Direct Calculation

$$T_{\text{Direct}}^{+}(t) = \frac{-A + \sqrt{A^2 - 4B \cdot \left(1 - \frac{\text{RTD}(t)}{R_0}\right)}}{2B}$$

Negative Temperature Simplified Approximation

$$T_{\text{Direct}}^{-}(t) = -241.96 + 2.2163 \text{RTD}(t) + 2.8541 \cdot 10^{-3} \cdot \text{RTD}(t)^2 - 9.9121 \cdot 10^{-6} \cdot \text{RTD}(t)^3 - 1.7052 \cdot 10^{-8} \cdot \text{RTD}(t)^4$$

RTD Sensor Output vs. Temperature (I_{source} = 100uA)



Digital Linearization Methods

Direct Computation

Bi-Section Method for Negative Temperatures

RTDError := 100 Res := 60.256 Tlow := -250 Thigh := 50

```
TBisection := | RTDTemp ← 0                                     = -99.999
                | while ( |RTDError| > 0.0001)
                |   | Tmid ←  $\frac{(Tlow + Thigh)}{2}$ 
                |   | Rcal ←  $100 \left[ 1 + A \cdot Tmid + B Tmid^2 + (Tmid - 100) \cdot C \cdot Tmid^3 \right]$  if Tmid < 0
                |   | Rcal ←  $100 \left( 1 + A \cdot Tmid + B \cdot Tmid^2 \right)$  if Tmid > 0
                |   | Rcal ← 0 if Rcal < 0
                |   | RTDError ← Res - Rcal
                |   | Tlow ← Tmid if RTDError > 0
                |   | Thigh ← Tmid if RTDError < 0
                |   | RTDTemp ← Tmid
                |   | return RTDTemp
```

T_{Bisection} = -99.999

Questions/Comments?

Thank you!!

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