Electrical, Computer & Energy Engineering
UNIVERSITY OF COLORADO BOULDER

# ECEN 5053-003 Homework Assignment

Course Name: Embedding Sensors and Actuators
Corresponding Module: C1M1
Week Number: 1
Module Name: Thermal Sensors

Note: Correct answer is in Blue Font

Homework is worth 100 points. Each question is worth 8.33 points.

Your Name: ***RUSHI JAMES MACWAN***

A. You are using a thermistor with a resistance of 5000Ω at 25.0 °C and with β = 3630. You measure a resistance of 921 ohms. What is the temperature in °C?
Answer: **73.11°C**

I10 | =ROUND(SUM((((1/(F6+273.15))+((LN(F7/F5))/F8))^(-1))-273.15),2)

**Answer - A (ESA Assignment)**

| Given Parameters | Notation | Value |
|---|---|---|
| Thermistor Base Resistance | $R_0$ (Ohms) | 5000 |
| Thermistor Base Temperature | $T_0$ (degree Celsius) | 25 |
| Measured Resistance | $R_t$ (Ohms) | 921 |
| Material Constant | $\beta$ (Kelvin) | 3630 |

| Parameters required to find | Notation |
|---|---|
| Measured Temperature (required) | T(degree Celsius) |

**Equation to be used**

$$T = \left(\frac{1}{T_0} + \frac{\ln\frac{R_t}{R_o}}{\beta}\right)^{-1}$$

**Calculation [ANSWER]**

T (degree Celsius) 73.11

*In this problem, I have used the equation focusing on how to find the temperature that is measured by the thermistor. I have presented the given values on the left side of the Excel File screenshot. The value T(degree Celsius) is the one that we are required to calculate. I have selected the box containing the answer so that the function is reflected at the top that I have used to calculate the answer. Lastly, I have rounded the answer to two significant digits.*

B. You are deciding between using a thermistor or a class A RTD for measuring the temperature of a critical circuit board of a smart phone near 25°C. The accuracy must be within 0.25°C throughout the range of measurement. Neither speed of response nor component cost is an issue.

What type of sensor do you use and why? Find an example online of a sensor that you could use for this application.

Answer:

*A thermistor suits better for the said problem than a class A RTD and is so due to several reasons as below:*

- *Thermistors have a specific temperature centric operating temperature.*
- *In this specific problem, we are required to work with a smartphone and a smartphone demands a narrow operating temperature range and therefore thermistor provides a better solution for accurate results since cost is not a problem.*
- *Thermistors have better sensitivity and very high stability and their inexpensive.*
- *RTDs on the other hand are big in size not usable for smartphones and consume a lot of power which is not suitable for a smartphone.*
- *On the other hand, the ample options of thermistors make them an ideal choice.*
- *The below given link shows one such thermistor for which the constraints are very desirable:* https://www.teamwavelength.com/download/Datasheets/tcs651.pdf
- *In this thermistor, the dissipation constant is 2-3 mW which is ideal and also provides an operating range of -6 to +67 °C at a very low current of micro 10 amperes which is very suitable for low powered devices like a smartphone.*

## FEATURES:

- Low Cost
- Small Size -- Conformally Coated
- Wide Resistance Range
- Available in 5 Different R-T Curves
- 1% Tolerance
- 3" Long Solid Nickel Wire Leads
- Teflon® Insulation Provides Isolation from Metal Housing
- RoHS Compliant (by exemption)

**Table 1. Sensor Comparison**

| | Thermistor | RTD | LM335 | AD592 |
|---|---|---|---|---|
| **Temp Range** | Within ~50°C of a given center temperature | -260°C to +850°C | -40°C to +100°C | -20°C to +105°C |
| **Relative Cost** | Very inexpensive | Most expensive | Moderately expensive | Moderately expensive |
| **Time Constant** | 6 to 14 seconds | 1 to 7 seconds | 1 to 3 seconds | 2 to 60 seconds |
| **Stability** | Very stable, ~0.0009°C | ~0.05°C | ~0.01°C | ~0.01°C |
| **Sensitivity** | High | Low | Low | Low |
| **Advantages** | • Durable<br>• Long lasting<br>• Highly sensitive<br>• Small size<br>• Lowest cost<br>• Best for measuring single point temp | • Best response time<br>• Linear output<br>• Widest operating temp range<br>• Best for measuring a range of temp | • Moderately expensive<br>• Linear output | • Moderately expensive<br>• Linear output |
| **Disadvantages** | • Nonlinear output<br>• Limited temp range<br>• Slow response time | • Expensive<br>• Low sensitivity | • Limited temp range<br>• Low sensitivity<br>• Large size | • Slowest response time<br>• Limited temp range<br>• Low sensitivity<br>• Large size |

*Courtesy: Wavelength Electronics*

*Link:*
[https://drive.google.com/open?id=1wH8QSZmTTpLl7izg2nc5rL3BY1t-wBeo](https://drive.google.com/open?id=1wH8QSZmTTpLl7izg2nc5rL3BY1t-wBeo)

C. A 100 ohm Class A RTD probe is calibrated at three points for extra precision, with a curve of RTD (T) = $RTD_0$ (1 + AT +$BT^2$ + $CT^3$(T -100)) where:

RTD (T) = the RTD element's resistance in ohms at temperature T
$RTD_0$ = the RTD element's resistance in ohms at 0°C
T = the RTD element's temperature in °C
A = 3.9083 x $10^{-3}$ /°C
B = -5.775 x $10^{-7}$ /°$C^2$
C = 0 if T >= 0°C

IF RTD(T) = 116.01 ohms, what is T?

Answer: **41.22°C**

ANS. C

$$RTD(T) = RTD_0\left[1 + AT + BT^2 + CT^3(T-100)\right]$$

$$\therefore \frac{RTD(T)}{RTD_0} = 1 + AT + BT^2 + CT^3(T-100)$$

Since, $C = 0$ if $T >= 0°C$,

$$\frac{RTD(T)}{RTD_0} = 1 + AT + BT^2$$

$$\therefore \boxed{BT^2 + AT + \left[1 - \frac{RTD(T)}{RTD_0}\right] = 0} \quad \text{—— ①}$$

Solving this Quadratic Equation:-

$$\Delta = \pm\sqrt{b^2 - 4ac} \quad (\text{with reference to } ax^2 + bx + c = 0)$$

(substituting Eq ①)

$$\therefore \boxed{\Delta = \pm\sqrt{A^2 - \left[4B\left(1 - \frac{RTD(T)}{RTD_0}\right)\right]}} \quad \text{—— ②}$$

Finally, solving the Quadratic Equation ① for T :- (using Eq②

$$\therefore \boxed{T = \frac{-A + \Delta}{2B}} \quad \text{—— ③}$$

I15 | =ROUND((SUM((((-1)*F7)+I11)/(2*F8))),2)

**Answer - C (ESA Assignment)**

| Given Parameters | Notation | Value |
|---|---|---|
| RTD element's resistance at 0 (degree Celsius) | $RTD_0$ (Ohms) | 100 |
| RTD element's resistance at T (degree Celsius) | $RTD_{(T)}$ (Ohms) | 116.01 |
| RTD Linearity Error Constant | A | 0.0039083 |
| RTD Linearity Error Constant | B | -5.775E-07 |
| RTD Linearity Error Constant | C | 0 |

| Parameters required to find | Notation |
|---|---|
| RTD element's temperature in degree Celsius) | $T_{(\text{degree Celsius})}$ |

**Equations to be used**

Please, refer the image attached with this answer.

**Calculation [ANSWER]**

| | |
|---|---|
| $\Delta_+$ | 0.003860697 |
| $\Delta_-$ | -0.003860697 |
| $T_{(\text{degree Celsius})+}$ | 41.22 |
| $T_{(\text{degree Celsius})-}$ | 6726.4 |

*In this problem, I have used the RTD 2nd order polynomial equation to find the value of the RTD element's temperature in °C. After carefully solving the Quadratic Equation, we get two values of the required temperature based on the Δ values for solving the Quadratic Equation.*

*Out of the two temperature values (answers) in °C, we select the* ***41.22°C*** *answer because the normal range of RTD temperature measurement lies between -260°C to 850°C according to one resource. The link to access that resource is given below. Secondly, the temperature of the surface of the Sun is approximately 5500°C. So, definitely it is impossible for the RTD to measure a temperature even greater than the temperature of the surface of the sun. Therefore, we eliminate the second option of 6726.4°C.*

*Thus, the required temperature is* ***41.22°C****.*

**Table 1. Sensor Comparison**

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| **Disadvantages** | • Nonlinear output<br>• Limited temp range<br>• Slow response time | • Expensive<br>• Low sensitivity | • Limited temp range<br>• Low sensitivity<br>• Large size | • Slowest response time<br>• Limited temp range<br>• Low sensitivity<br>• Large size |

*Courtesy: Wavelength Electronics*

*Link:*
[https://drive.google.com/open?id=1wH8QSZmTTpLI7izg2nc5rL3BY1t-wBeo](https://drive.google.com/open?id=1wH8QSZmTTpLI7izg2nc5rL3BY1t-wBeo)

D. You are using a Type K thermocouple to measure the temperature of a process that operates in the range of 1000°C to 1100°C. In particular, you know that the thermoelectric voltage is 42.053 mV at 1020°C and 42.440 mV at 1030°C. Having no other data in between, and no way to look up the data on thermocouple tables, what is a good approximation for the thermoelectric voltage at 1027°C?

Answer: **42.16 mV**

ANS. D

Given: $T_{min}$, $T_{max}$, $V_{min}$, $V_{max}$

$$\therefore \boxed{slope = \frac{V_{max} - V_{min}}{T_{max} - T_{min}}} \quad \text{—— (1)}$$

Now, for given voltage T which has to be calculated :-

$$\frac{V - V_{min}}{T - T_{min}} = slope$$

$$\therefore \boxed{V = [(slope) \times (T - T_{min})] + V_{min}} \quad \text{—— (2)}$$

Answer is in milli Volts.

I13 | =ROUND(SUM((I11*(F7-F5))+F8),2)

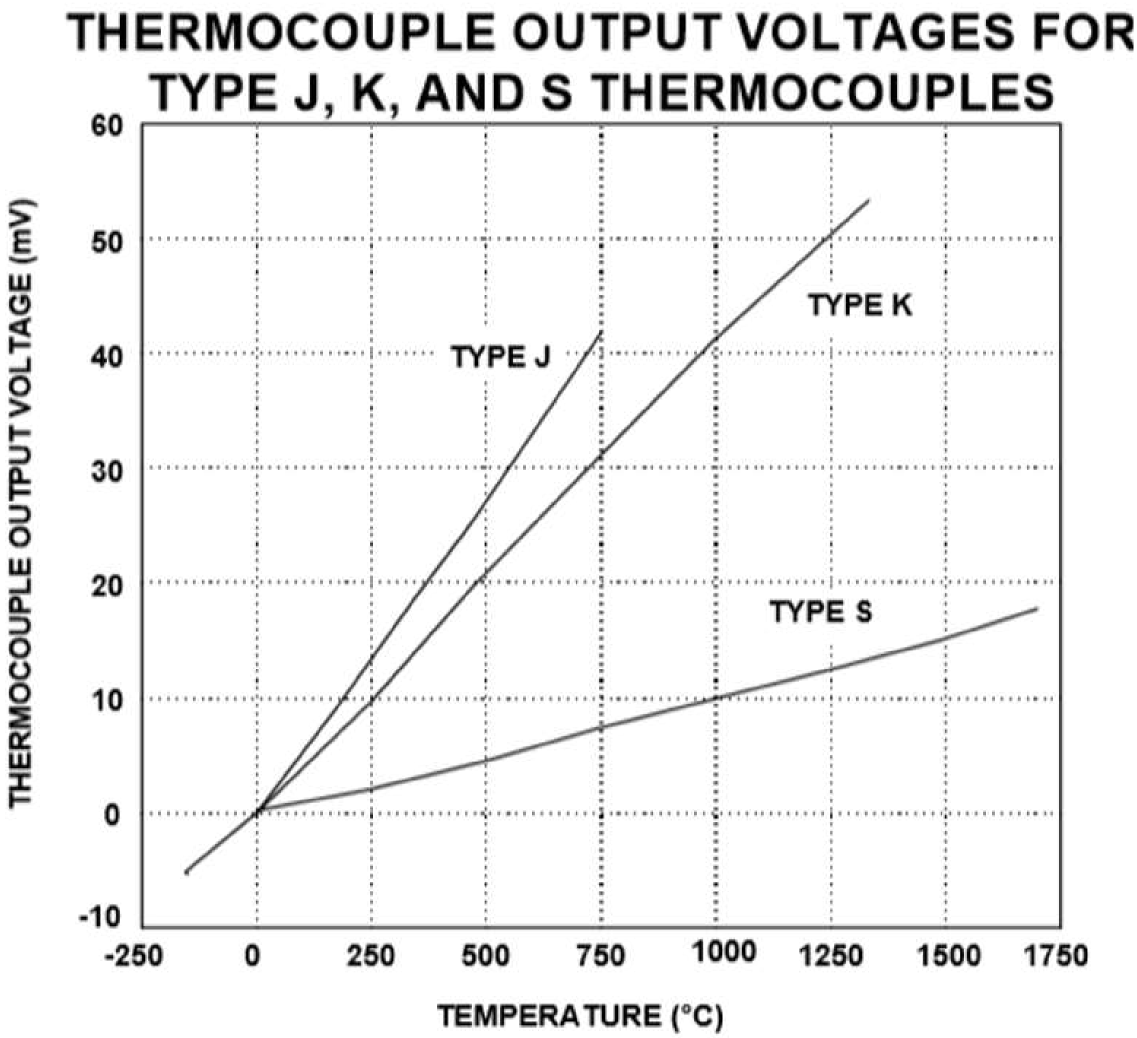
**Answer - D (ESA Assignment)**

| Given Parameters | Notation | Value | Parameters required to find | Notation |
|---|---|---|---|---|
| Temperature range - Min (degree celsius) | $T_{min}$ | 1000 | Voltage corresponding to given temperature (mV) | V |
| Temperature range - Max (degree celsius) | $T_{max}$ | 1100 | | |
| Given Temperature (degree celsius) | T | 1027 | | |
| Voltage corresponding to Temp range - Min (mV) | $V_{min}$ | 42.053 | | |
| Voltage corresponding to Temp range - Max (mV) | $V_{max}$ | 42.44 | | |

| Equations to be used | Calculation [ANSWER] | |
|---|---|---|
| Please, refer the image attached with this answer. | Slope | 0.00387 |
| | V (mV) | 42.16 |

*In this problem, two different values of thermoelectric voltage corresponding to two different temperatures for a Type-K Thermocouple have been provided. Having said that there is no other day in between nor the use of look-up table is available, the thermoelectric voltage for a given temperature can be approximated using the concept of the T-V curves for a Type-K Thermocouple. It has been shown that for a Type-K Thermocouple, the temperature varies linearly with the thermoelectric voltage (given in mV).*

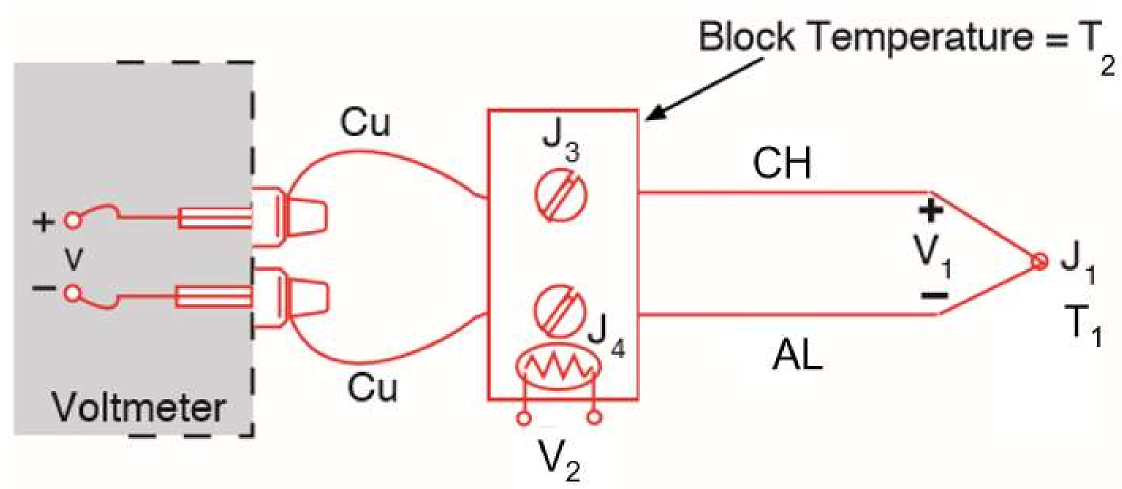
*Therefore, in this problem, I have used the line equation. First, I use the given data to find the slope of the linearity between the temperature and the thermoelectric voltage (in mV) and then using the slope and one set of value that we already have, I have calculated the required thermoelectric voltage which amounts to* ***42.16 mV****.*




*Courtesy: Class Lecture Slide (C1M1V9)*

E. You are using a Type K thermocouple to measure the temperature of a semiconductor etch process that operates in the range of 1000°C to 1100°C. The thermistor in your isothermal block (junctions J3 and J4) measures a temperature of 20°C and your voltmeter measures 44.240 mV. What is the temperature $T_1$ of your process?

Answer: **1056°C**




*In this problem, using the Thermocouple construction as was explained in the class (the image above was portrayed in the class slides), the following points need to be followed to obtain the required constraint: $T_1$ which is the answer.*

1. *First, the thermistor in the isothermal block at the junctions J3 and J4 measures a temperature of 20°C. <u>This is the $T_2$ temperature.</u>*
2. *It is further said that the voltmeter measures 44.240 mV <u>which is the $V$ voltage</u>.*
3. *Since, <u>we need to find $T_1$</u>, we have to use the following equation:*
   $$V_1 = V - V_2$$
   *From the data provided, we already have $T_2$ and so we can calculate $V_2$ using $T_2$ from the <u>look-up table</u>. The image of the look-up table is as below:*

ITS-90 Table for type K thermocouple

Thermoelectric Voltage in mV

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.000 | 0.039 | 0.079 | 0.119 | 0.158 | 0.198 | 0.238 | 0.277 | 0.317 | 0.357 | 0.397 |
| 10 | 0.397 | 0.437 | 0.477 | 0.517 | 0.557 | 0.597 | 0.637 | 0.677 | 0.718 | 0.758 | 0.798 |
| 20 | 0.798 | 0.838 | 0.879 | 0.919 | 0.960 | 1.000 | 1.041 | 1.081 | 1.122 | 1.163 | 1.203 |
| 30 | 1.203 | 1.244 | 1.285 | 1.326 | 1.366 | 1.407 | 1.448 | 1.489 | 1.530 | 1.571 | 1.612 |
| 40 | 1.612 | 1.653 | 1.694 | 1.735 | 1.776 | 1.817 | 1.858 | 1.899 | 1.941 | 1.982 | 2.023 |

   *From this table, we get <u>$V_2 = 0.798$ mV.</u>*

4. *Using, the values of $V$ and $V_2$, we get $V_1$ as under:*
   $V_1 = V - V_2 = (44.240 - 0.798)$ mV = <u>43.442 mV</u>.

5. *Again, using the look-up table for the Type K Thermocouple using the below given link, we find out T1.* [https://srdata.nist.gov/its90/download/download.html](https://srdata.nist.gov/its90/download/download.html)

*Thus,* ***T1 = 1056°C****.*

ITS-90 Table for type K thermocouple

Thermoelectric Voltage in mV

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 | 41.276 | 41.315 | 41.354 | 41.393 | 41.431 | 41.470 | 41.509 | 41.548 | 41.587 | 41.626 | 41.665 |
| 1010 | 41.665 | 41.704 | 41.743 | 41.781 | 41.820 | 41.859 | 41.898 | 41.937 | 41.976 | 42.014 | 42.053 |
| 1020 | 42.053 | 42.092 | 42.131 | 42.169 | 42.208 | 42.247 | 42.286 | 42.324 | 42.363 | 42.402 | 42.440 |
| 1030 | 42.440 | 42.479 | 42.518 | 42.556 | 42.595 | 42.633 | 42.672 | 42.711 | 42.749 | 42.788 | 42.826 |
| 1040 | 42.826 | 42.865 | 42.903 | 42.942 | 42.980 | 43.019 | 43.057 | 43.096 | 43.134 | 43.173 | 43.211 |
| 1050 | 43.211 | 43.250 | 43.288 | 43.327 | 43.365 | 43.403 | 43.442 | 43.480 | 43.518 | 43.557 | 43.595 |
| 1060 | 43.595 | 43.633 | 43.672 | 43.710 | 43.748 | 43.787 | 43.825 | 43.863 | 43.901 | 43.940 | 43.978 |
| 1070 | 43.978 | 44.016 | 44.054 | 44.092 | 44.130 | 44.169 | 44.207 | 44.245 | 44.283 | 44.321 | 44.359 |
| 1080 | 44.359 | 44.397 | 44.435 | 44.473 | 44.512 | 44.550 | 44.588 | 44.626 | 44.664 | 44.702 | 44.740 |
| 1090 | 44.740 | 44.778 | 44.816 | 44.853 | 44.891 | 44.929 | 44.967 | 45.005 | 45.043 | 45.081 | 45.119 |

F. Suppose we include the lead resistance in the calculation of temperature for a class A RTD. If $R_3$ = 1000 ohms, $R_a$ = 20 ohms, $V_0$ = 1.75 volts, and V = 5 volts, what is the nominal temperature measured. Given the tolerances, what is the highest temperature you could measure?

Answer: **157.17°C** and **157.63434°C**

*In this problem, using the knowledge of the circuit analysis for RTD as explained in the class slides (C1M1V8), I have used the below given equation to calculate the resistance of the RTD to further calculate the nominal temperature corresponding to that resistance. The notation for the required resistance of the RTD is $R_t$.*

ANS. F

$$R_t = [R_3 + R_a]\left[\left(\frac{1}{(V_0/V) + (1/2)}\right) - 1\right] - R_a$$

Putting the values we get $R_t$ which is the RTD resistance corresponding to the nominal temperature.

*Furthermore, after calculating the thermistor resistance $R_t$ which corresponds to the nominal temperature, we use the below given equation to calculate the nominal temperature $t$.*

$$R_t = \mathrm{R}\left[1 + At + Bt^2\right]$$

*In this equation, $R$ is the RTD element's resistance at 0°C which we assume to be 100 (ohms) for the case of a class A RTD. Calculating as given below, we get the nominal temperature $t$.*

Ans. F

$R_t$ = Thermistor resistance corresponding to nominal temperature

$R$ = RTD element's resistance at 0°C

$\therefore R_t = R\left[1 + At + Bt^2\right]$

$\therefore \frac{R_t}{R} = 1 + At + Bt^2$

$\therefore Bt^2 + At + \left[1 - \frac{R_t}{R_o}\right] = 0$ — (1) Quadratic Equation

$\therefore \Delta = \pm\sqrt{A^2 - 4(B)\left[1 - \frac{R_t}{R_o}\right]}$ — (2) Roots

Finally, using quadratic eq. (form:- $ax^2 + bx + c = 0$)

$$\boxed{t = \frac{-A + \Delta}{2B}}$$ — (3)

Nominal temperature = $t$

Now, for tolerance, for class A RTD,

$\therefore$ The tolerance is

$\pm(0.15 + (0.02t))$°C (according to IEC 60751)

$\therefore$ Max temp = $\boxed{\left(t + \left[0.15 + (0.02t)\right]\right) \text{°C}}$ — (4)

Max temp given tolerances

```
I10    =ROUND(SUM(((-F13)+L10)/(2*F14)),2)
```

**Answer - F (ESA Assignment)**

| Given Parameters | Notation | Value |
|---|---|---|
| | $R_3$ (Ohms) | 1000 |
| | $R_a$ (Ohms) | 20 |
| | $V_0$ (volts) | 1.75 |
| | V (volts) | 5 |

| Parameters required to find | Notation |
|---|---|
| Nominal Temperature | $t_+$ (degree Celsius) |
| Thermistor required Resistance | $R_t$ (Ohms) |

**Equation to be used**

$$R_t = R\left[1 + At + Bt^2\right]$$

| | | |
|---|---|---|
| RTD Linearity Error Constant | A | 0.0039083 |
| RTD Linearity Error Constant | B | -5.775E-07 |
| RTD Linearity Error Constant | C | 0 |
| RTD element's resistance at 0 (degree Celsius) | R (Ohms) | 100 |

**Calculation [ANSWER]**

| | | | |
|---|---|---|---|
| $t_+$ (degree Celsius) | 157.17 | $\Delta_+$ | 0.003726769 |
| $t_-$ (degree Celsius) | 6610.45 | $\Delta_-$ | -0.003726769 |
| $R_t$ (Ohms) | 160 | | |

*As per the above calculation, we select the positive root $\Delta_+$ since the negative root leads to a very unstable temperature which is represented by $t_-$ and therefore the nominal temperature is $t_+$ which is **157.17°C**.*

*Further, to find the highest measurable temperature, given the tolerances, based on the formula below, we calculate the highest measurable temperature:*

| | IEC 60751 | ASTM 1137 |
|---|---|---|
| **Class A** | ± [0.15 + (0.002 · t)] °C | ± [0.13 + (0.0017 · t)] °C |
| **Class B** | ± [0.30 + (0.005 · t)] °C | ± [0.25 + (0.0042 · t)] °C |

*Therefore, the **highest temperature** will be:*

*= (t + [0.15 + (0.002*t)]) °C*
*= (157.17 + [0.15 + (0.002*157.17)]) °C*
*= **157.63434°C***

*The links to the documents that I have used to frame this answer are as under:*

*Courtesy links:*

https://www.omega.com/Temperature/pdf/RTDSpecs_Ref.pdf

https://drive.google.com/open?id=1T_ZtGplUGo4ySX5jtGmtPTkqycBQDFgZ

G. Why do we use a 3rd order polynomial to calibrate an RTD below 0°C, but only a 2nd order polynomial to calibrate an RTD above 0°C?

Answer:

*There is a relation between the resistance and temperature of any RTD which is given by an equation named: Callendar-Van Dusen equation.*

*This equation is given as follows:*

*RT = R0 [1 + A*T + B*T2 – (T – 100)*C*T3]*

*Where,*

*RT is resistance of RTD at a given temperature T*
*R0 is the RTD element's resistance at 0°C*

*Here, A, B, and C are constants and their values are given by following equations:*

*A = α + ((α*δ) / 100)*
*B = – ((α*δ) / 1002)*
*C = – ((α*β) / 1004)*

*These constants are known as Callendar-Van Dusen constants.*

*Furthermore, α, β, and δ are the constants which are obtained by the mathematical equations provided by the Callendar-Van Dusen theory which are as below:*

*α = (R100 – R0) / (100 + R0)*
*δ = ([R0*{1 + (α260)}] – R200) / (4.16α*R0)*

*Here, it is important to understand that β can be only found empirically and is constant at temperatures less than 0°C. But, with temperatures rising above 0°C, the value of β becomes zero. As per the equation of Callendar-Van Dusen, the constant C also repeats the same process as it turns out to be zero for temperatures greater than or equal to zero degree Celsius. This implies that for all temperatures higher than 0°C, the equation becomes a 2nd order polynomial from a 3rd order polynomial equation as can be seen from the above provided equations. This explains the reason behind the presence of only a 2nd order polynomial equation for temperatures above 0°C for calibrating an RTD.*

H. You are deciding between using a type K thermocouple or Class A RTD for measuring the temperature of steam between 250°C to 500°C. The accuracy must be within 2.5°C throughout the range of measurement. Your acceptable speed of response is 2 seconds. What type of sensor do you use?

Answer:

*A Type K Thermocouple would suit better for solving this problem than a Class A RTD and that is so due to several reasons as mentioned below:*

- According to IEC 60751 standards, the maximum temperature that can be measured for a Type A RTD is 300°C and this has been mentioned in one of the documents. The link to these documents are as under:

  https://www.omega.com/Temperature/pdf/RTDSpecs_Ref.pdf

  https://reotemp.com/wp-content/uploads/2015/11/TBRTDTOL-0614RTDToleranceClasses.pdf

- A class A RTD will have slower response time than a type K thermocouple. This can be often longer than what is permissible: 2 seconds for this problem. To support this argument, the below given links bring some articles into picture that have some compelling technical information on the same.

  https://www.omega.co.uk/temperature/z/thermocouple-RTD.html

  https://www.acromag.com/sites/default/files/Comparison_of_Thermocouple_and_RTD_Temperature_Sensors_918A.pdf

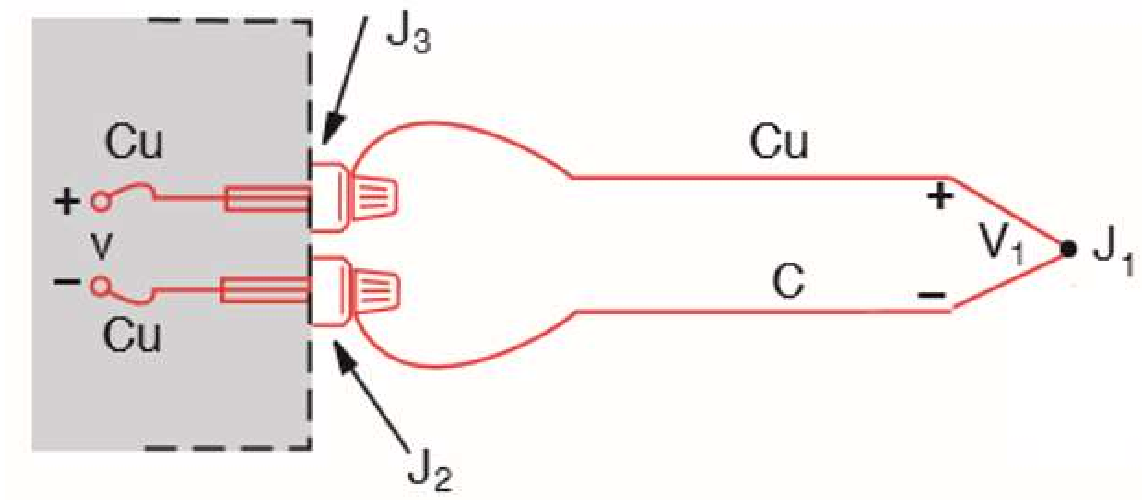
- A type K Thermocouple on the other hand provides all the required services: accuracy of 2°C at 500°C and a response time that is within the prescribed limit: 2 seconds. This strengthens my decision to stay with a type K thermocouple.

- For reference, one of the Class A RTD available online represents that it's response time is way higher than the prescribed deadline: 3 seconds. Secondly, the operation range stretches only upto 300°C which is not apt for the circumstances presented in this problem.

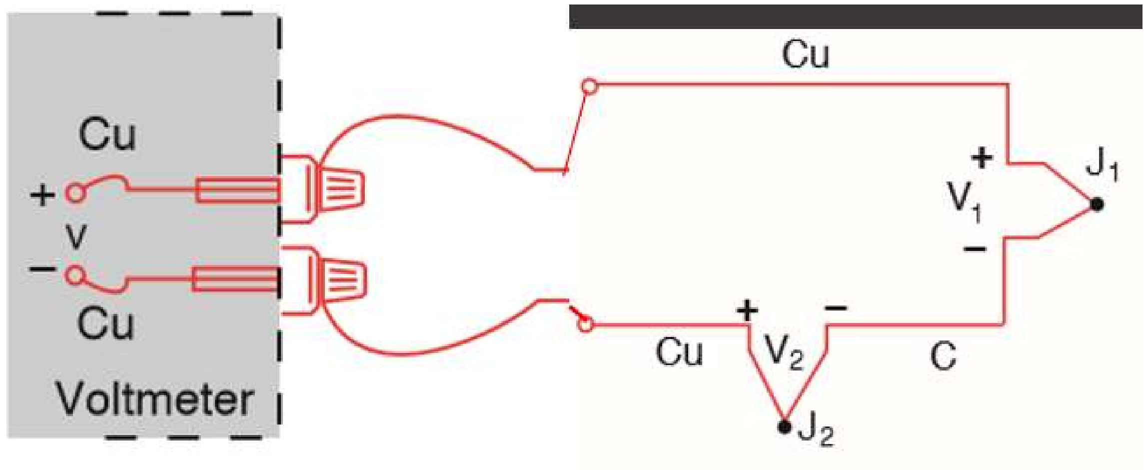
https://www.heraeus.com/media/media/group/doc_group/products_1/hst/m_sensors/us_3/M222_HST-USA.pdf

I. In our explanation of how thermocouples work we added a copper lead wire at junction J2 in our thermocouple circuit for a type T thermocouple. Why did we do this?

Answer:




*As can be seen from this T type thermocouple diagram that we are required to read V1 in order to gain the temperature of the source. Further, by connecting the copper leads of the voltmeter, we create a junction J2 (Cu-C) and therefore to read the V1 data, we add a copper lead wire at junction J2 so that we create a Cu-Cu junction at the voltmeter.*

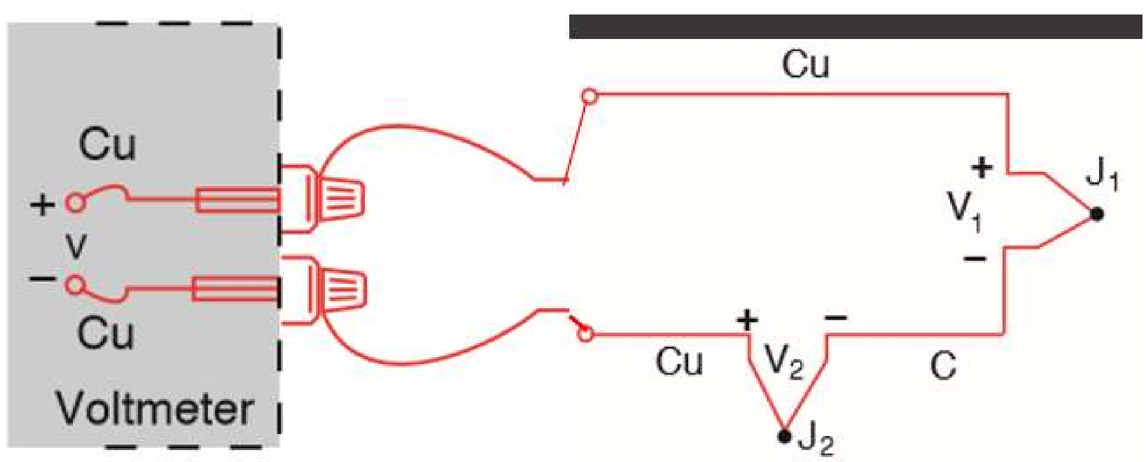



*Once this junction is created, as per the above image, we can calculate the isothermal voltage V2 which is obtained by using the potential that is created between Cu-C at junction J2 which helps us to calculate the voltage V which finally provides us with the V1 value.*

J. In our explanation for how people originally used Type T thermocouples, why did they put junction J2 in a bucket of ice?

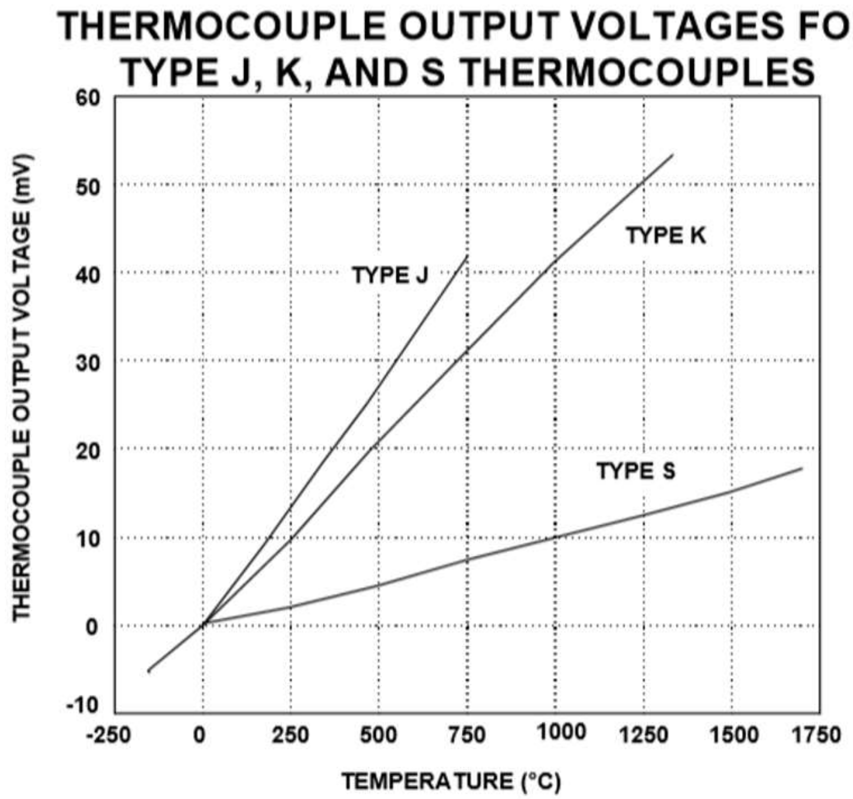
Answer:

*The junction J2 is put in a bucket of ice because once this is done, the temperature at junction J2 becomes 0°C. Furthermore, this helps us in directly calculating the temperature at the source which is T1 at the junction J1 since the junction J2 constraints are eliminated. This can be understood using the below given circuit and the equations that follow it.*




$$V = V_1 - V_2 = b\,(T_{J1} + 273^\circ\ K) - b\,(273^\circ\ K) = bT_{J1}$$

*Here, directly using the readings taken by the voltmeter which provides the V voltage, we can directly calculate the junction J1 source temperature which is written as T1. This can be done by looking at the look-up table to find the slope value for a given thermocouple which gives b and therefore the required temperature Tj1.*




K. A type K thermocouple datalogger uses a thermistor to measure the cold junction temperature. It has a resistance of 2252Ω at 25.0 °C, with β = 3630, and with a tolerance of +/- 0.2°C. You measure a resistance of 1120 ohms.

The voltmeter in the datalogger measures 48.395 mV. Given the tolerances for the thermistor and thermocouple, what is the highest temperature that the datalogger would read in °C?

Answer: **1141°C**

*To solve this problem, first we calculate the temperature measured by the thermistor using the given data as under:*

Ans K. Thermistor Calculation:-

$$T = \left[ \frac{1}{T_0} + \frac{\ln(R_t/R_o)}{\beta} \right]$$

$R_o = 2252\,\Omega$ Tolerance $= \pm 0.2°C$

$T_o = 25°C = 298.15K$ $R_t = 1120\,\Omega$

$\beta = 3630K$

*Once the required temperature is measured, all we need to do is to subtract the tolerance 0.2°C value from this calculated temperature.*

*Thus, the required temperature is: (T – 0.2) °C*

*This is because, if this temperature is lower, the voltage drop at the thermistor junction of the said thermocouple is lower. Further, the lower this voltage drop is at the thermistor junction the higher the voltage is of the thermocouple. The higher this voltage is the higher the final temperature is. This is the required temperature which is the highest temperature the datalogger would read.*

I10 =ROUND(SUM((((1/(F6+273.15))+((LN(F7/F5))/F8))^(-1))-273.15),2)

**Answer - K (ESA Assignment)**

| Given Parameters | Notation | Value |
|---|---|---|
| Thermistor Base Resistance | $R_0$ (Ohms) | 2252 |
| Thermistor Base Temperature | $T_0$ (degree Celsius) | 25 |
| Measured Resistance | $R_t$ (Ohms) | 1120 |
| Material Constant | $\beta$ (Kelvin) | 3630 |

| Parameters required to find | Notation |
|---|---|
| Measured Temperature (required) | T(degree Celsius) |

**Equation to be used**

$$T = \left( \frac{1}{T_0} + \frac{\ln \frac{R_t}{R_o}}{\beta} \right)^{-1}$$

**Calculation [ANSWER]**

| | |
|---|---|
| **T** (degree Celsius) | 43.15 |

*Further, we subtract the tolerance from this $T$°C and therefore the answer will be:*

*= (T – 0.2) °C = (43.15 - 0.2) °C =* ***42.95 °C = 43°C (approx.)***

*Using the look-up table, we receive the corresponding voltage.*

ITS-90 Table for type K thermocouple

Thermoelectric Voltage in mV

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.000 | 0.039 | 0.079 | 0.119 | 0.158 | 0.198 | 0.238 | 0.277 | 0.317 | 0.357 | 0.397 |
| 10 | 0.397 | 0.437 | 0.477 | 0.517 | 0.557 | 0.597 | 0.637 | 0.677 | 0.718 | 0.758 | 0.798 |
| 20 | 0.798 | 0.838 | 0.879 | 0.919 | 0.960 | 1.000 | 1.041 | 1.081 | 1.122 | 1.163 | 1.203 |
| 30 | 1.203 | 1.244 | 1.285 | 1.326 | 1.366 | 1.407 | 1.448 | 1.489 | 1.530 | 1.571 | 1.612 |
| 40 | 1.612 | 1.653 | 1.694 | 1.735 | 1.776 | 1.817 | 1.858 | 1.899 | 1.941 | 1.982 | 2.023 |

*From this, we get the voltage which is* ***$V_2$ = 1.735 mV***.

*Now, using the Thermocouple equation, $V_1 = V - V_2$, we find the V1 voltage which is the required Thermocouple voltage corresponding to the highest datalogger temperature.*

*Here, $V$ = 48.395 mV (given)*

*$V_2$ = 1.735 mV*

*So, $V_1 = V - V_2$ = (48.395 – 1.735) mV =* ***46.66 mV***

*Again, using the look-up table, we get the corresponding temperature which is the required highest datalogger temperature that it would read.*

ITS-90 Table for type K thermocouple

Thermoelectric Voltage in mV

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 | 41.276 | 41.315 | 41.354 | 41.393 | 41.431 | 41.470 | 41.509 | 41.548 | 41.587 | 41.626 | 41.665 |
| 1010 | 41.665 | 41.704 | 41.743 | 41.781 | 41.820 | 41.859 | 41.898 | 41.937 | 41.976 | 42.014 | 42.053 |
| 1020 | 42.053 | 42.092 | 42.131 | 42.169 | 42.208 | 42.247 | 42.286 | 42.324 | 42.363 | 42.402 | 42.440 |
| 1030 | 42.440 | 42.479 | 42.518 | 42.556 | 42.595 | 42.633 | 42.672 | 42.711 | 42.749 | 42.788 | 42.826 |
| 1040 | 42.826 | 42.865 | 42.903 | 42.942 | 42.980 | 43.019 | 43.057 | 43.096 | 43.134 | 43.173 | 43.211 |
| 1050 | 43.211 | 43.250 | 43.288 | 43.327 | 43.365 | 43.403 | 43.442 | 43.480 | 43.518 | 43.557 | 43.595 |
| 1060 | 43.595 | 43.633 | 43.672 | 43.710 | 43.748 | 43.787 | 43.825 | 43.863 | 43.901 | 43.940 | 43.978 |
| 1070 | 43.978 | 44.016 | 44.054 | 44.092 | 44.130 | 44.169 | 44.207 | 44.245 | 44.283 | 44.321 | 44.359 |
| 1080 | 44.359 | 44.397 | 44.435 | 44.473 | 44.512 | 44.550 | 44.588 | 44.626 | 44.664 | 44.702 | 44.740 |
| 1090 | 44.740 | 44.778 | 44.816 | 44.853 | 44.891 | 44.929 | 44.967 | 45.005 | 45.043 | 45.081 | 45.119 |
| 1100 | 45.119 | 45.157 | 45.194 | 45.232 | 45.270 | 45.308 | 45.346 | 45.383 | 45.421 | 45.459 | 45.497 |
| 1110 | 45.497 | 45.534 | 45.572 | 45.610 | 45.647 | 45.685 | 45.723 | 45.760 | 45.798 | 45.836 | 45.873 |
| 1120 | 45.873 | 45.911 | 45.948 | 45.986 | 46.024 | 46.061 | 46.099 | 46.136 | 46.174 | 46.211 | 46.249 |
| 1130 | 46.249 | 46.286 | 46.324 | 46.361 | 46.398 | 46.436 | 46.473 | 46.511 | 46.548 | 46.585 | 46.623 |
| 1140 | 46.623 | 46.660 | 46.697 | 46.735 | 46.772 | 46.809 | 46.847 | 46.884 | 46.921 | 46.958 | 46.995 |

*Thus, the corresponding highest data-logger temperature is* ***1141°C***.

L. Go to Google Patents (www.patents.google.com) and download US patent 6,344,747. Read the patent and answer the following questions:

Q.1 In this patent why is the diagnostic element needed?

A.1.

*The diagnostic element is an integral part of this patent. This is because this patent is focusing on the solution to monitor the state of a thermocouple over a prolonged period of time. With time, the states are compared at different intervals to understand the damage or deformation in the process. The thermocouple must be tested and kept in check while it in use and this is a quintessential thing in the real industry. Therefore, the thermocouple with two or more thermoelements has multiple diagnostic elements connected at the common junction points and there can be a case where the thermocouple can may only have one diagnostic element. This diagnostic element when connected with a thermoelement forms a connected measurement loop which provides resistance or impedance values which can be easily measured to detect the condtion of the thermocouple in question. Therefore, a diagnostic element is used and is the required element in this patent.*

Q.2 What is the main feature required for the diagnostic element?

A.2

*For a diagnostic element, the primary requirement is that it should be relatively more stable and less prone to undergo a change in its resistance as a result of the operational stress than the thermoelement(s). However, it is also preferable to have a diagnostic element that is less prone to the change in the resistance under operational stresses than the thermoelement(s) that it is connected with as per this patent document.*

Q.3 How is the diagnostic element connected into the thermocouple circuitry?

A.3

*In the various embodiments of this patent, the diagnostic element is connected with the thermoelement(s) by properly welding the common junctions. Further, these element loops are coupled to the measurement electronics which periodically measures the resistance or the impedance of each of the various thermoelement(s) for the changes in the resistances or impedances at a certain temperature.*

Q.4 What are two reasons the patent says that thermocouples degrade over time?

A.4

*Over time, thermoelements may suffer changes in composition due to various operational stresses. Such changes may result in the thermocouple not providing a true temperature. Compositional changes are referred to generally by the term degradation. Degradation can result in the thermoelement providing inaccurate temperature measurements. This degradation can occur as the metals are subjected to a lot of cycles of resistance change. This can lead a thermoelement to suffer irreversible degradation. An operator of a temperature-dependent process may be able to recognize that degradation has occurred because the operator may intuitively know that the temperature reading being supplied by the thermoelement is outside the normal range of temperatures at which the process operates.*

*Furthermore, while manufacturing those thermoelements, impurities can be a part of it which is then used to form a thermocouple that is used for various industries. These impurities can lead to some resistance stress which alters the actual anticipated structure of the thermoelement(s) in a thermocouple which eventually results into the thermocouple being faulty.*

Q.5 Why can the diagnostic elements be used to detect changes in the resistance of the thermocouple wires?

A.5

*In operation, a diagnostic element and thermoelement form a measurement loop around which a resistance or impedance measurement can be made to check if a thermocouple has any defects. Further, in the process of using a thermocouple, an initial loop resistance is measured and established as a reference or baseline. The loop is then monitored while the thermocouple is in operation for changes in loop resistance. Normally, changes in the loop resistance are an accurate indicator of thermoelement degradation. Thus, we can record the changes in the thermocouple and therefore detect the changes in the resistance/impedance of the thermoelements and therefore we can detect the defects in the thermocouple.*