# Mechanical Measurements and Metrology
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## Module - 2
## Lecture - 11
## Thermoelectric Thermometry

This will be lecture number 11 on Mechanical Measurements. In the previous lecture, that is lecture number 10, we were discussing some details about thermoelectric thermometry or the use of thermocouples for the measurement of temperature. We were in fact discussing the Kelvin relations which relate the three effects: the Peltier; the Thomson; and the Seebeck effects.

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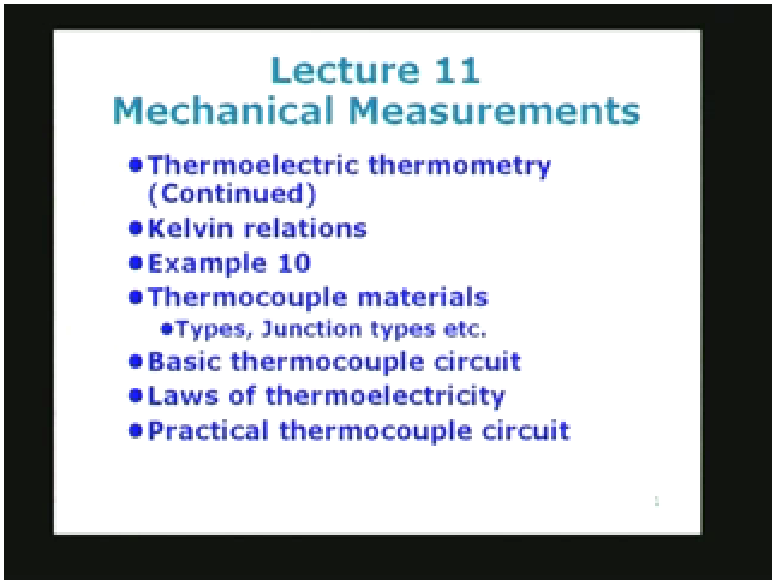

Lecture 11
Mechanical Measurements

- Thermoelectric thermometry (Continued)
- Kelvin relations
- Example 10
- Thermocouple materials
  - Types, Junction types etc.
- Basic thermocouple circuit
- Laws of thermoelectricity
- Practical thermocouple circuit

We have two relations between these three quantities, all the Kelvin relations, and we were just discussing how to obtain the Kelvin relations, and then we were looking at some details of what follows from these relations. So in this present lecture what I am going to do is continue from there and I will go back to the Kelvin relations and discuss it more fully, and then I will take an example where I am going to show how the Kelvin relations are going to be useful in describing the characteristic of the thermocouple, specific thermocouple. Then we will discuss something about thermocouple materials, the types of materials we use, the method of making junctions, and so on. These are all very practical aspects of thermometry, thermocouple thermometry, and then we will also discuss in relation to the fundamental thermoelectric laws we have discussed in the last lecture.

We will discuss about the basic thermal thermocouple circuit and some of the practical aspects of thermocouple circuits bringing in what we call as laws of thermoelectricity.

Just to recapitulate, the Kelvin relations were derived in the last lecture and I just want to recapitulate by writing them down here.

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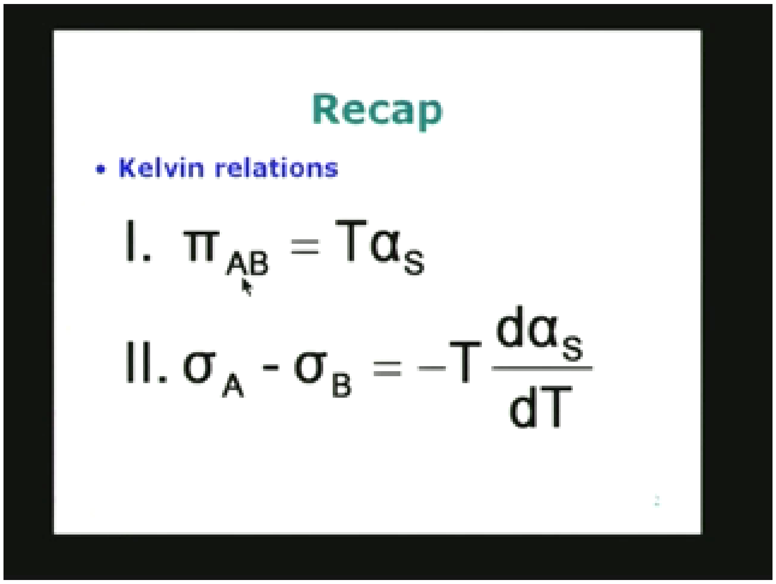

## Recap

- **Kelvin relations**

I. $\pi_{AB} = T\alpha_S$

II. $\sigma_A - \sigma_B = -T\dfrac{d\alpha_S}{dT}$

The first one is pi$_{AB}$, the Peltier coefficient or Peltier effect cocoefficient, AB is the pair of materials were chosen, material A and material B is equal to the absolute temperature T times the Seebeck coefficient alpha subscript s. For this is the first Kelvin relation.

The second Kelvin relation relates the Thompson heat sigma A minus sigma B. This is the difference in the Thompson coefficients in the two materials that is equal to negative of the temperature absolute temperature d alpha$_s$ by dT.

Just remember that these were derived with the two junctions held at very close temperatures to each other. One of them has T, another one is T plus dT. There was a small difference in temperature, and therefore, these are differential in nature. And what we have is a relationship between alpha s, the Seebeck coefficient, again it is coming here, the pi, the Peltier coefficient, and the sigmas, which are the Thompson coefficients. So, if you look at this and look at what I am going to show in the next slide I am expecting that there is a certain relationship between the Seebeck voltage and the temperature.

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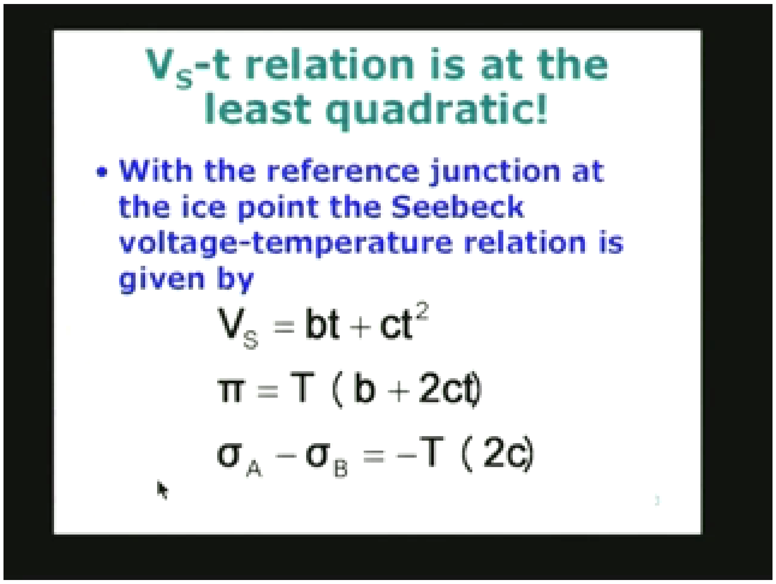

### $V_S$-t relation is at the least quadratic!

- With the reference junction at the ice point the Seebeck voltage-temperature relation is given by

$$V_S = bt + ct^2$$

$$\pi = T\ (b + 2ct)$$

$$\sigma_A - \sigma_B = -T\ (2c)$$

From now onwards I am going to use two different temperatures. Capital T will be representing the Kelvin temperature or the absolute temperature, the Kelvin scale, and I will also use the lower case t for the temperature in degree Celsius. So when ever I use the capital T it is understood that I am referring to the absolute temperature. When I use the lower case t, I am representing, or referring to the Celsius temperature.

In practice, normally what we do is we hold one of these junctions at the ice point, and we will call it as reference junction, and the measuring junction is the other junction which is going to be used, which is going to be exposed, is the temperature we are going to measure. So, before going to the thermocouple circuitry aspects which will come a little later let us assume that there are two junctions, the measuring junctions, between a and b at a temperature lower case t, which is degree Celsius, and the reference junction is at a temperature equal to 0 degree Celsius corresponding the ice point.

I can represent the $V_s$ -t relation by requiring that at least it will be a quadratic, because if you go back to the previous slide, I see that there is the Peltier coefficient is proportional to alpha$_s$. Alpha is nothing but ds $dV_s$ by dT. It is the rate of change of $V_s$ with respect to the temperature, therefore, this is the first derivative of the $V_s$ with respect to the temperature, and because sigma A minus sigma B is related to d alpha$_s$ by dT which is actually second derivative of $V_s$ with respect to the temperature if you think in terms of a Taylor expansion around the temperature T we should at least have three terms in that expression.

Of course, the first term which corresponds to constant will be 0, because I am taking the reference temperature at 0. That means, you can see here (Refer Slide Time 6:36) if I put t equal to 0, this should be 0, this should be 0, $V_s$ equal to 0. So, I am requiring if the measuring junction is at the ice point, there should be no output, and therefore, I am going to take it as vt plus ct square. This is the minimum we should have. In fact in practice, we usually go for the fourth degree polynomial or even higher degree polynomial depending on the requirement.

So, using $V_s$ equal to bt plus ct squared pi, I am now dropping the suffix AB. If you want you can put it back here. Pi is equal to T times alpha; alpha is nothing but the differentiation of $V_s$ with respect to the temperature, and now in the Kelvin relationship, we were using only the capital T. As far as the derivative is concerned whether you take derivative with respect to capital T or lower case t is of no significance it will be the same. Therefore, I will take it as t into (Refer Slide Time 7:33) $dV_s$ by dt where t is the lower case temperature, that will be differentiating that I get b plus 2 ct. And sigma A minus sigma B the difference in the Peltier the Thomson heat is equal to minus T times d pi d alpha d $alpha_s$ by dt and d alpha $_s$ by dt is nothing but 2c. That is the coefficient.

So actually, b plus 2cT you differentiate once more you get 2c. These are the three relations now. That means, you can see here that b and c are related to the pi and the sigmas. Therefore the Seebeck voltage which is appearing as voltage across the thermocouple junctions is related to the first term which comes because of the Peltier effect and the second term which comes because of the Thompson effect. You will also notice the following.

If for some reason sigma A minus sigma B is very small, that is, if the Thomson effect in the two conductors A and B are close to each other this will in fact be very small, and therefore, the term containing ct square and this will be small. Here c is equal to you can say sigma A minus sigma B divided by minus T, and if c is minus 2T, and c will be small if sigma A minus sigma B is small then you have a true linear temperature relationship between the Seebeck voltage and the temperature. So we do expect in practice that c will be much smaller than b depending on the combination of materials we have chosen so that we have very nearly nonlinear relationship, but for large temperature range the nonlinear effect is going to become important. So with this background, let us take a look at a simple example.

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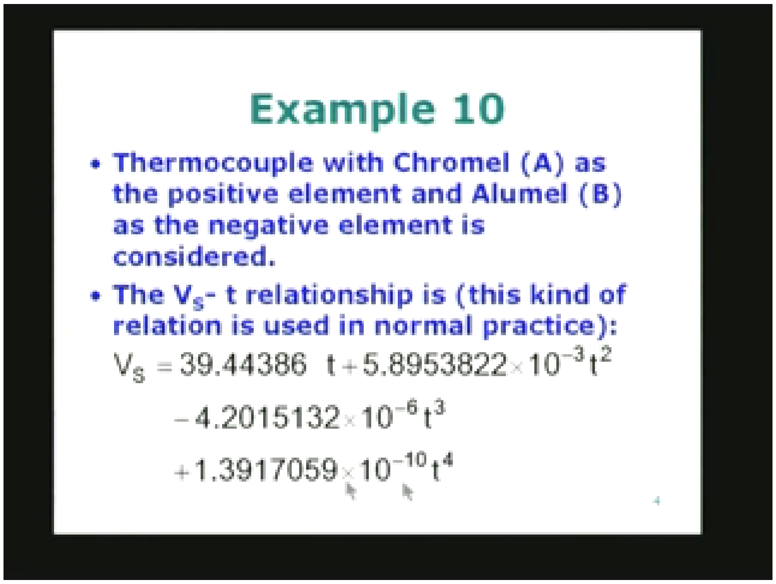

## Example 10

- Thermocouple with Chromel (A) as the positive element and Alumel (B) as the negative element is considered.
- The $V_S$- t relationship is (this kind of relation is used in normal practice):

$$\begin{aligned} V_S &= 39.44386\ t + 5.8953822 \times 10^{-3} t^2 \\ &\quad - 4.2015132 \times 10^{-6} t^3 \\ &\quad + 1.3917059 \times 10^{-10} t^4 \end{aligned}$$

So, I am taking a thermocouple in which I am choosing the material A to be material called chromel (I will come back to the materials little later on) and the positive element will be chromel A and the element B of the negative element will be alumel. These two are alloys of different materials put together metallic alloys. Now I am going to consider this combination, and I will give you the $V_s$-t relationship of these two combinations which is obtained from the references. So the $V_s$-t relationship is represented in this form. This is normal practice.

In this case, I am representing it as the fourth degree polynomial. So you can see that $V_s$ is equal to 39.44386 t where t is in degree Celsius, $V_s$ is in microvolts, plus 5.89 etc into 10 to the power of minus 3 into t square. It is a quadratic term. This is related to the alpha. This is related to the derivative of the alpha, as we have just seen from the Kelvin relationship. And then we have minus 4.20 etc into 10 to the power of minus 6 into t cube, plus 1.3917 etc, into 10 to the power of minus 10 into t to the power of 4. This is the expression which is expected to give a good representation of the Seebeck effect in chromel alumel thermocouple pair where the reference junction is maintained at the ice point. With this back ground, let us just apply the Kelvin relationships and I am going to look at what is happening near t equal to 0.

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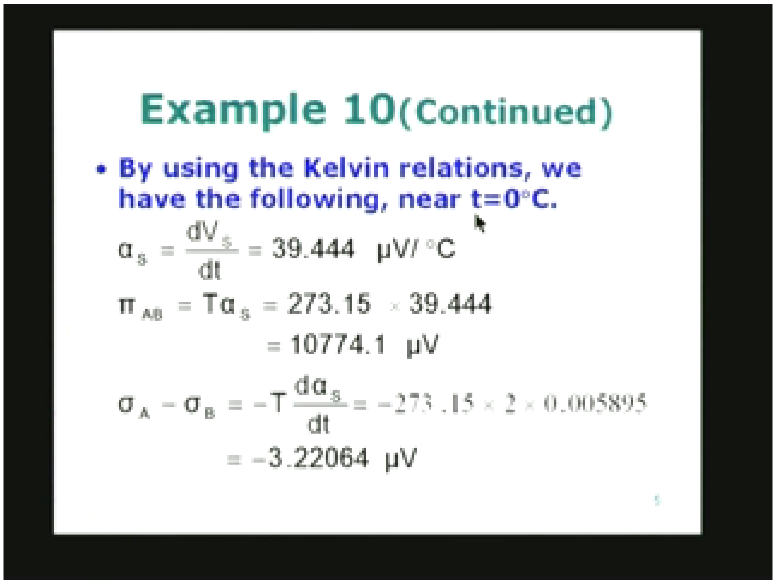

## Example 10(Continued)

- **By using the Kelvin relations, we have the following, near t=0°C.**

$$\alpha_S = \frac{dV_S}{dt} = 39.444 \quad \mu V/°C$$

$$\pi_{AB} = T\alpha_S = 273.15 \times 39.444$$
$$= 10774.1 \quad \mu V$$

$$\sigma_A - \sigma_B = -T\frac{d\alpha_S}{dt} = -273.15 \times 2 \times 0.005895$$
$$= -3.22064 \quad \mu V$$

I am going to look at near t equal to 0. This corresponds to 273.15 for the Kelvin value and alpha $_s$ is equal to dV$_s$ by dt, all you have to do is to go back to the previous slide and take the derivative with respect to temperature and then put t equal to 0 in that, lower case t equal to 0, and upper case T equal to 273.15, and what I will get is dV$_s$ by dt is equal to 39.444. I have simply rounded it of, microvolts per degree Celsius. This is the value of alpha. This is Seebeck coefficient for the material A,B being chromel, alumel near t equal to 0.

Of course, the alpha value is going to change with temperature, as you can see there is 4 degree polynomial. This will not be constant. It will slowly vary with respect to temperature. Now, the Kelvin relation we also have pi AB where A and B are chromel and alumel is equal to t alpha and alpha is already determined here so t is 273.15 into 39.444. This will give you 10,774.1 microvolt. So, the Peltier coefficient is quite a big sizeable quantity.

If you look at the Thomson coefficients for these materials, sigma A minus sigma B, this comes from the second Kelvin relations, minus T d alpha$_s$ by dt and d alpha$_s$ by dt is nothing but you obtain the derivative by taking the second derivative (Refer Slide Time 13:10) of this expression put t equal to zero in that and I will get (Refer Slide Time 13:20) minus 273.15 into d alpha$_s$ by dt is nothing but 2 into 0.005895, and that will give you minus 3.22064 microvolts. So, what we notice from here is that this is the alpha, is about 39 microvolts per degree Celsius. This is the Seebeck coefficient for chromel alumel pair.

The Peltier coefficient is pretty large, equal to 10 to the power of 10,000, a little more than 10,000, close to eleven thousand microvolts, and the difference between the Thompson effects in the two wires is rather small. That means that the behavior near t equal to 0 will be more or less linear with these two becoming important. Now let us look at the different thermoelectric materials which are available.

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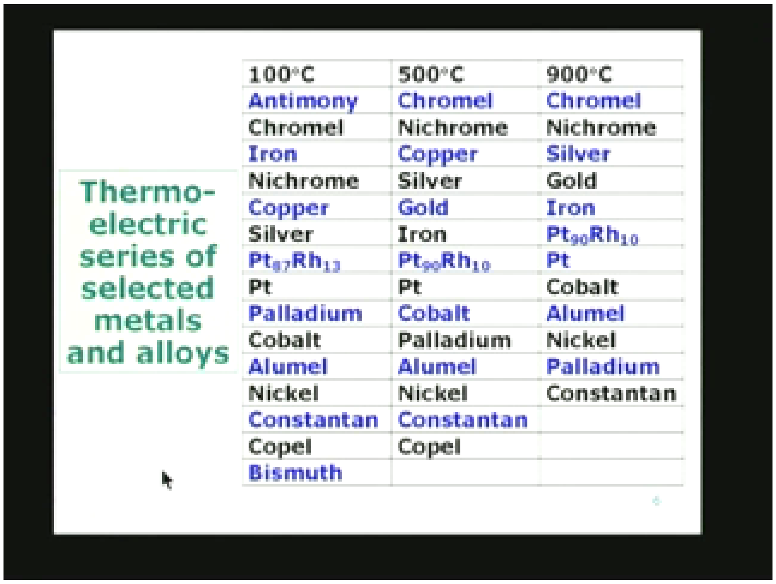

Thermo-electric series of selected metals and alloys

| 100°C | 500°C | 900°C |
|---|---|---|
| Antimony | Chromel | Chromel |
| Chromel | Nichrome | Nichrome |
| Iron | Copper | Silver |
| Nichrome | Silver | Gold |
| Copper | Gold | Iron |
| Silver | Iron | $Pt_{90}Rh_{10}$ |
| $Pt_{87}Rh_{13}$ | $Pt_{90}Rh_{10}$ | Pt |
| Pt | Pt | Cobalt |
| Palladium | Cobalt | Alumel |
| Cobalt | Palladium | Nickel |
| Alumel | Alumel | Palladium |
| Nickel | Nickel | Constantan |
| Constantan | Constantan | |
| Copel | Copel | |
| Bismuth | | |

In fact, in practice, what we do is we standardize some thermocouples and we use only those thermocouples, even though in principle any two materials, any two metals, or any two alloys can be joined together to form a thermocouple, it is simply not possible to do that in practice, because it leads to a lot of confusion, and each person will have his own thermocouple, and so on. It is not a very satisfactory state of affairs.

Just to look at some of the thermocouple materials which are available, materials and alloys, I will just put them in the following order. If you look at this column for example, 100 degrees means this is the temperature range in which these materials can be used. 500 degrees here means these can be used up to 500 degrees. The materials shown in column 3 can be up to 900, and many more. So, the three columns tell us the range of temperatures in which these materials can be used.

Second information which comes from this particular table is that, if you take antimony which is the first one in this in the first row or the second row and if you compare with the any of the materials which are shown below, that this will be positive with respect to all of that. That is, if I take antimony and chromel, if I make a junction between these two the voltage appearing across the two will be positive on the antimony side and the chromel will be negative.

So, how do we come to conclusion regarding this? It is arranged in the more positive to the top and less positive or negative more negative to the bottom. So that is the order in which they appear, and usually, what is done in practice is to use platinum as the reference material and all thermal thermoelectric emfs are measured with respect platinum as the negative element.

For example, here if I take platinum and cobalt, platinum is negative element in general but you see that cobalt is actually negative with respect to platinum. The sign of the voltage will be changed. For example, platinum and constantan if I take, some where here you can see that is more negative than platinum, but platinum is used as the negative element and all thermal thermoelectric information is given with respect to platinum as the negative element, and therefore, when I use two different materials not one of them not being platinum.

For example, in the earlier case I had chromel and alumel, what I will be doing is I will be taking the difference between the thermoelectric voltages for alumel with respect to platinum and then chromel with respect to platinum and take the difference between these two that will give the total output of that thermocouple. These details are not very essential right now. All I want to do is to look at some of the materials, antimony and bismuth.

In fact, when Seebeck was trying to discover or trying to look at thermoelectric phenomena, he had actually chosen antimony and bismuth, and you see that antimony and bismuth are at the top and the bottom of this table. That means that the output from an antimony-bismuth thermocouple will be the largest of any thermocouple pairs you can take from here. If you take, for example, very close to each other, silver and platinum rhodium, or even platinum, rhodium and platinum, this will be a very small output because they are very close to each other.

So, if you want a large Seebeck effect, choose the material from as close to the top of the table as possible and choose the material as close to the bottom of the table as possible. These are all the principles we used. Actually we will see later there some of the commonly employed thermocouples, one which I talked about earlier is chromel alumel you can see chromel is number two here alumel is almost at the bottom. This is a very common one. If I take iron and constantan that also is very large gap. If you take copper and constantan also there is a large gap. So you see that if you choose the materials properly you can get sizeable Seebeck effects.

So the three columns as I said, are representative of materials which can be used in different temperature ranges and I don’t want to go into each one of these. You can see the materials and you can see that a large number of materials are in fact available for making thermocouples. Now, with this background, let us look at some of the standard thermocouple pairs which are normally used in practice.

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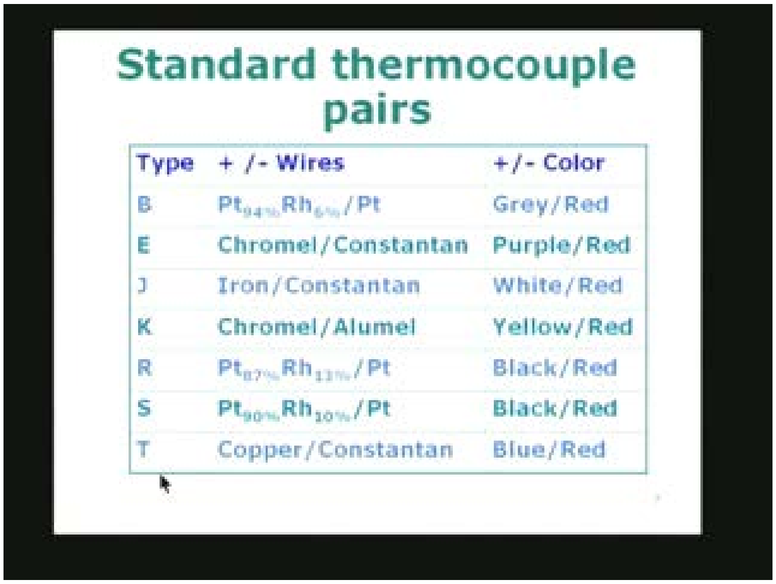

## Standard thermocouple pairs

| Type | + /- Wires | +/- Color |
|---|---|---|
| B | $Pt_{94\%}Rh_{6\%}/Pt$ | Grey/Red |
| E | Chromel/Constantan | Purple/Red |
| J | Iron/Constantan | White/Red |
| K | Chromel/Alumel | Yellow/Red |
| R | $Pt_{87\%}Rh_{13\%}/Pt$ | Black/Red |
| S | $Pt_{90\%}Rh_{10\%}/Pt$ | Black/Red |
| T | Copper/Constantan | Blue/Red |

So, before we look at this standard thermocouple pairs let me just say that, this standardization has been done by the manufacturers, by the users, by the scientists, all coming together and deciding that these are the materials we are going to use, and the manufacturers are able to give long length of wires made up of these materials of the highest purity, whatever is required for thermocouple thermometry practice, and therefore, it is a cooperation between the manufacturers, the metallurgist, the users like ourselves, and the scientists who look into the basics of thermometry and so on. All of them coming together have decided that these are the materials we are going to use normally. Does it mean that we should not use the other materials? No.

In case you have a certain need you can always have your own thermocouple pair and you have to calibrate it and so on and you can you are welcome to use that, but, if you are going to use thermocouples as a standard method formation temperature in the laboratory it is better to go for this standard ones which are available off the shelves from various manufacturers, from various countries, and it is readymade and you don’t have to really spend your time looking at their performance, characteristics, and so on. These are also available in the standard form from the manufacturers data.

So, what are the different types we have and the color code? So the types are given alphabetical names BEJKRS and T. These are the different symbols which are used. So, if I look at the B type thermocouple the positive wire will be 94% platinum, 6% rhodium alloy, and the negative element will be platinum. That’s what I mean by plus slash minus wires means the plus is first, after the slash comes the negative element. So platinum rhodium 94 6 versus platinum, the color of the platinum rhodium thermocouple wire will be grey that means it is going to be covered with a sheath or a jacket in grey color, the negative element is going to be red.

In fact, if you see in this table the entire negative elements are going to have the same color red and therefore immediately you can recognize when you look at a thermocouple cable that the one which is red is the negative and the one which is not red but some other color is going to be positive element.

Next one is chromel constantan. Let me just go back to the previous (Refer Slide Time 21:41) slide. You see that chromel constantan ,the advantage of chromel constantan is it is coming from the top most to the bottom most, and you will also see that chromel can be used at 100, 500, 900. That means that I can use it even at 900 degrees. So, entire range of temperature I can cover, therefore, chromel constantan has got a large Seebeck effect, Seebeck coefficient, and also, it can be used over extended range of temperatures. So it is called E-type. E-type means chromel is the positive element, constantan is the negative element. The color of the positive element is purple, red is negative, then J is the iron constantan.

Again, if you go back to the previous slide you will see that iron is very close to the top and the constantan is at the bottom. This also gives you sizeable output. In fact, chromel constantan, iron constantan, chromel alumel, and also the copper constantan all have very high Seebeck coefficients. Only thing is E-type can be used to high temperatures, K- type can be also used to cover very large temperature range, but copper constantan is limited to low temperatures only.

Therefore, even though they are all similar in their characteristic as well as the Seebeck effect is concerned, which means that they have a large output for a given temperature the different ranges can be covered using these thermocouples. So E-type chromel constantan, I will quickly go through the entries here. J is iron constantan, K is chromel alumel. This is a very useful thermocouple. K is almost universal in this application. It can be used from below room temperature up to about 1300 or more degrees Celsius, and therefore, it is a very common thermocouple which is used by everybody, almost, if we don't know what the thermocouple is made of, chances are that it is going to be chromel alumel thermocouple, yellow and red. So, the positive element is yellow and the red is the negative element. Then, there are some which are specifically meant for high temperature thermometry.

R,S, these two, are specifically useful for high temperature measurement, so platinum 87, rhodium 13 versus platinum black and red platinum 87, platinum 13, rhodium element is black and platinum is red, this is useful for very high temperatures. The point to notice that if I go back to the previous slide you see platinum is here platinum rhodium is right here and the output is very small, that means they are very close to each other in this table and because of that because of the proximity you are going to have very small Seebeck effect but the advantage is that it can cover a very large temperature range. Therefore, you don't expect a very large output, but you expect it to be useful for a large temperature range. This is always the problem.

If some instrument has got a large range, usually it will be limited in some other sense, and in this case also you will see that it is the large range but it is going to be less sensitive. Sensitive means the amount of voltage you get for a unit degree difference between the hot and cold junction that is nothing but the Seebeck coefficient. Seebeck coefficient is very small for platinum rhodium platinum thermocouple as compared to the E-type, and now I leave the symbols E-type for example immediately you should know that it is chromel constantan and so on. So, the R type and the S-type both we used platinum rhodium different compositions, 90, 10, or 87, 13 versus platinum or both of them use black as the color code for the positive element, red for the negative element. And the T type thermocouple is also very common, especially if we are interested in temperature range below 400 degrees Celsius. It is very commonly used in practice, and if one is using thermocouples in normal laboratory practice practically every thing can be done with K and T type thermocouples themselves. It is very seldom that we may required the other thermocouples, excepting when the temperature levels are very high.

In fact, there are other materials, other pairs, which are not very standard. They are used once in a while. So I am going to look at them in the next slide.

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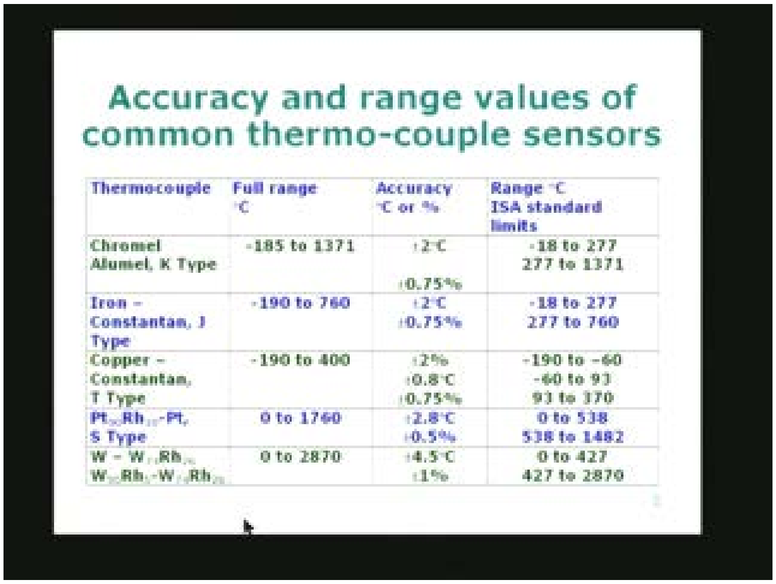

## Accuracy and range values of common thermo-couple sensors

| Thermocouple | Full range °C | Accuracy °C or % | Range °C ISA standard limits |
|---|---|---|---|
| Chromel Alumel, K Type | -185 to 1371 | ±2°C<br>±0.75% | -18 to 277<br>277 to 1371 |
| Iron – Constantan, J Type | -190 to 760 | ±2°C<br>±0.75% | -18 to 277<br>277 to 760 |
| Copper – Constantan, T Type | -190 to 400 | ±2%<br>±0.8°C<br>±0.75% | -190 to -60<br>-60 to 93<br>93 to 370 |
| Pt[illegible]Rh[illegible]-Pt, S Type | 0 to 1760 | ±2.8°C<br>±0.5% | 0 to 538<br>538 to 1482 |
| W – W[illegible]Rh[illegible]<br>W[illegible]Rh[illegible]-W[illegible]Rh[illegible] | 0 to 2870 | ±4.5°C<br>±1% | 0 to 427<br>427 to 2870 |

So I am giving some accuracy range value for common thermocouple sensors the type chromel alumel K- type can be used between minus 185 to about 1371, very large temperature range, and the accuracy is plus or minus 2 degree Celsius in this range, and it can also be used between two ranges, minus 18 to 277 and 277 to 1371, this plus or minus point 75% corresponds to the second range. The J type thermocouple iron constantan minus 190 to plus 760, then you see the numbers here which are characteristic of the accuracy you can expect with this copper constantan at T type minus 190 to plus 400. You see that there are three different ranges minus 190 to minus 60.

Actually, you can see that it covers are very wide range from the negative side also below the room temperature minus 190 to minus 60 plus or minus 2% percent, minus 60 to 93 plus or minus point 8 degrees, and then 93 to 370.75% plus minus. Then we have the S-type which is a high temperature thermocouple pair, Pt 90 Rh 10 versus Pt S-type. It can be used between 0 and 1760 degrees Celsius, very wide range of temperatures plus or minus point 5%. That’s what we expect between 538 and 1482 plus or minus 2.8 degrees with 0 and 538. Then there is a very special type of thermocouple which uses tungsten versus tungsten rhodium different compositions, tungsten 95, rhodium 5, tungsten 74, rhodium 26, tungsten versus tungsten 74, rhodium 26. So these are two special thermocouple pairs.

The range of temperature is 0 to 2870, very high temperatures. That is the advantage of this and the accuracy is obtainable above plus or minus 5 degrees, 4.5 degrees, or plus or minus 1%, depending on the range. So, what do we learn from this table?
We learn from the table that you cannot you do not expect the temperature to be measured very accurately because there are inherent inaccuracies in the measurement and therefore we will be happy if these numbers which are given in these tables are achieved.

So now, let us look at how to represent the data for a thermocouple pair. I am taking an example of a K- type thermocouple pair which is chromel alumel, and in this case the information is available in two different forms you can use.

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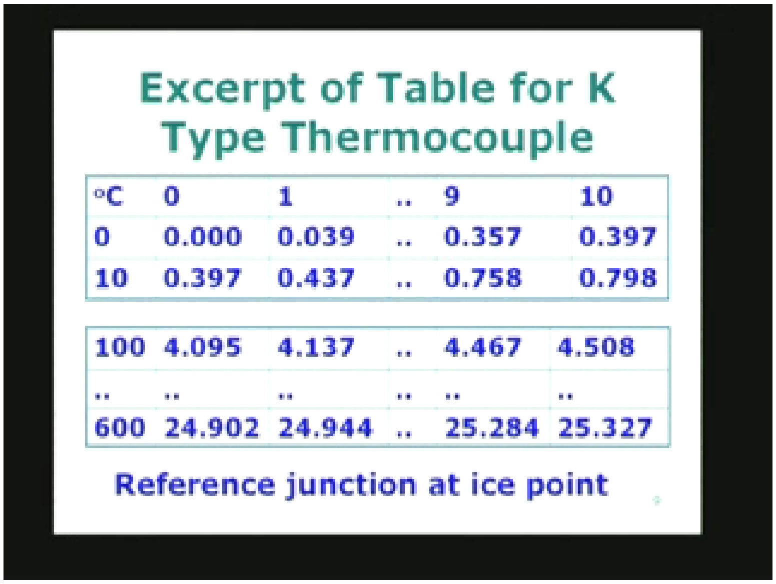

### Excerpt of Table for K Type Thermocouple

| °C | 0 | 1 | .. | 9 | 10 |
|---|---|---|---|---|---|
| 0 | 0.000 | 0.039 | .. | 0.357 | 0.397 |
| 10 | 0.397 | 0.437 | .. | 0.758 | 0.798 |
| 100 | 4.095 | 4.137 | .. | 4.467 | 4.508 |
| .. | .. | .. | .. | .. | .. |
| 600 | 24.902 | 24.944 | .. | 25.284 | 25.327 |

Reference junction at ice point

One is in the form of a table, and I have taken the excerpt from a table for K- type thermocouple. The table is constructed like this: the first column is degrees Celsius. In the first column it goes by 0, 10, 20 like that. It goes in steps of 10 degrees. And the other columns it is goes by steps of 1 degree. So you can see 0, 1, then there is a gap here, that means 2, 3, 4, 5, 6, 7, 8, then 9, 10. I have taken some portion of the table, that means there are several columns which are just shown by two dots here, and let us look at the kind of information you get from the table.

The reference junction is always at the ice point, therefore, if the measuring junction is also at 0 degrees you expect 0 voltage. No output if the reference junction and the measuring junction are at the same temperature and in this case they are at the ice point. Then, if it is the 1 degree difference point 039 if you remember 39 microvolts, we had already alpha $_s$ value near t equal to 0, we calculated earlier in example 10. So, this point 039 is nothing but 39 microvolts, or point 039. This is millivolts. What we are given here is millivolts. Then point 357, point 397 and again it starts, 10, 11 up to 20, so point 397 goes up to point 798, and there is a gap here, there are many more entries, then I take a 100 degrees, I get about 4.095, or about 401 millivolts is what you expect from a K- type thermocouple when the temperature difference between the two junctions is equal to, it is the same as the steam point minus the ice point, 100 degrees is the steam point at 1 atmospheric pressure and 0 degrees is the ice point. The difference between these two is 100 degrees, you get about 5 millivolts.

So now you also realize that if we want to use the thermocouple the kind of voltage difference or the potential difference we should be able to measure is in millivolts, and if the range is, let us say, 0 to 600 in this case the maximum output you are going to get about 25 millivolts, the minimum is about 0 millivolts here, about 25 millivolts. So you can choose the proper instrument to measure the potential difference. These potentiometers are the voltage measuring devices are available in different ranges and so on, or, you may buy one which contains several ranges and use the appropriate range for the each one of the ranges of temperature.

If you are measuring between 0 and, that is, 100 volts, you put into zero into 5 millivolt range. If it is 100, if it is up to 600 then of course you require up to 25 millivolts. And of course, it can go up if you go above. If you remember the K- type thermocouple can be used up to about 1350 degrees Celsius. It can be, table will be going up to that value. So what happens if you go close to that you exceed that temperature is that the temperature material the material of the thermocouple is not going to be stable, it will undergo either a chemical change or a physical change and therefore thermocouple becomes useless. So, the useful range of the thermocouple is determined by the properties of the material, one is thermoelectric properties, the second is the physical properties of the material.

If the material becomes not unusable because it melts or it becomes soft, and so on, then that is the temperature up to which you can use it. Obviously, the thermocouple with tungsten and tungsten aeon you can see it is melting point is very very high and therefore we are able to use it up to about 2000, 3800 and what ever number was given earlier. So, the K - type thermocouple characteristically looks like this. If I make a plot for the range from 0 to 1350 are given.

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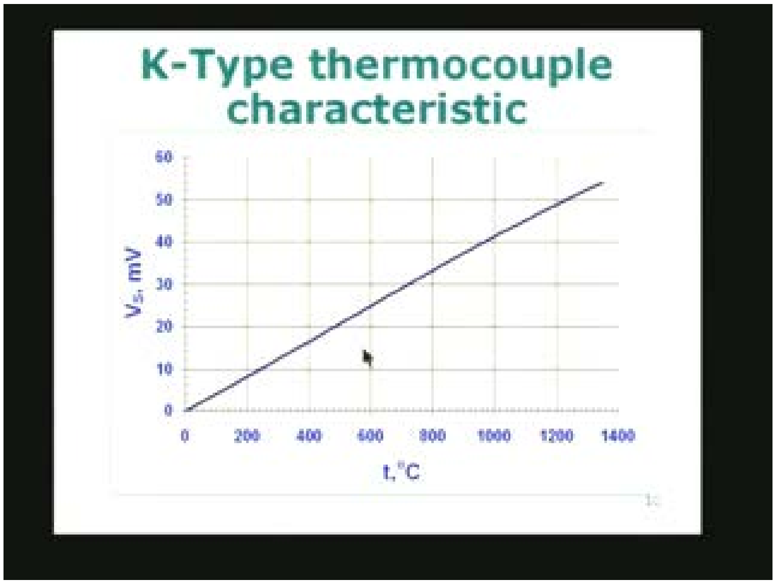

K-Type thermocouple characteristic

Therefore, if you go through, look at this one, if you were to draw a straight line it will go somewhere like that. Therefore, there is a slight nonlinearity and that is because of the 4 degree polynomial I am going to use for representing the data, and you can also see that at about 1350 degrees, you get something more than 50 millivolts as the output. A very sizeable output, and it can be easily measured by most of the modern instruments, so the performance, the characteristic which is given here is the same as what is given in the form of a table. I have just made a plot of the same information.

There are two ways of doing it, one is give a table then make a plot of a Seebeck voltage versus temperature with the ice point as the reference junction, or I can represent the information in the form of a polynomial which was given in example 10 earlier, $V_s$ equal to something multiply by t plus t square plus t cube t to the power of four. This is one way of representing the information. There are two ways in which we are going to use the information given either in the table form or in the form of a plot or in the form of a polynomial.

We will be measuring the application where we are going to use the thermocouple to measure the temperature, we are measuring the voltage, so I know the $V_s$, I don’t know the temperature. If I am going to use the polynomial in this form $V_s$ equal to a function of temperature like this, it is going to be very difficult, because I have to find a value for t which corresponds to this and which gives the value of $V_s$ ,I have measured. Therefore, what I am going to do is I am also going to represent an inverse relationship between temperature as a function of $V_s$.

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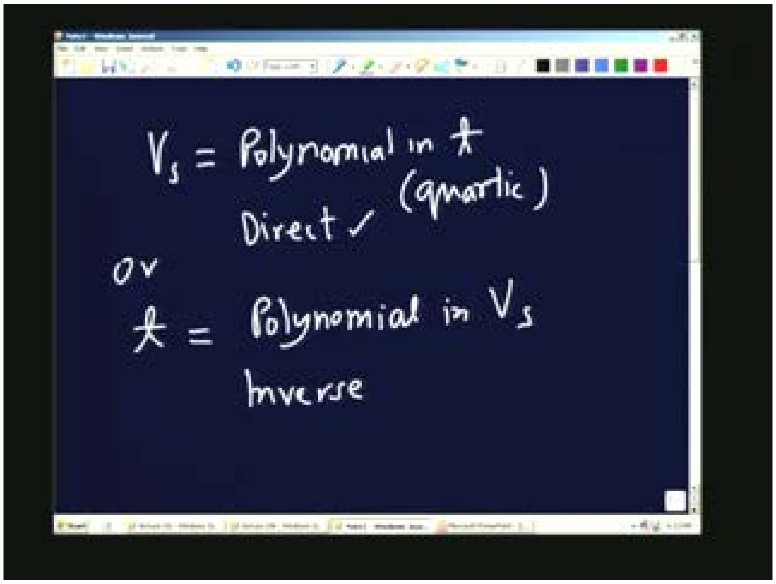

$V_s$ = Polynomial in $t$ (quartic)

Direct ✓

or

$t$ = Polynomial in $V_s$

Inverse

So, just to indicate how it is done let me just look at this. One way of doing it is to, if you remember we had $V_s$ is equal to a polynomial in t. We had a quartic, actually a quartic that means that the polynomial was degree 4. We can also have t is equal to a polynomial in $V_s$, so we can call this as the direct relationship, and this is the inverse relationship. So, it is always better to have these two relations so that we can either do this for the direct calculation, that is, you want to find out what is the Seebeck voltage for a given temperature, or you can use the second one to find out what is the temperature corresponding to the voltage which has been measured in the experiment.

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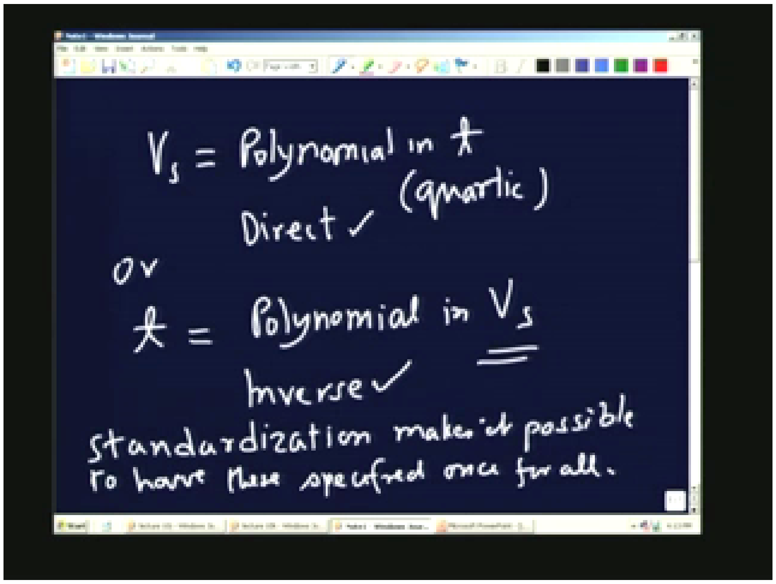

$V_s$ = Polynomial in $t$ (quartic)

Direct ✓

or

$t$ = Polynomial in $\underline{\underline{V_s}}$

Inverse ✓

standardization makes it possible to have these specified once for all.

In fact, the standardization, let us just write it here, standardization makes it possible to have these specified once for all. That is, the manufacturer is going to make the thermocouple wires using standard materials of high purity. He is going to conduct either, by himself, some experiments, or he is going to subject his material to experimentation in the standardization laboratory. In the standardization laboratory, the procedure of measuring temperature according to ITS 90 will be followed, and they are going to calibrate the thermocouple by using several fixed points, and after obtaining this these values of the Seebeck voltages at several fixed points, a polynomial is fit using the regression methods.

We have already regression analysis methods which we have already indicated earlier when we were talking about data analysis, so those polynomials are once for all given, and they are available in the form of documents where, for each particular, each type of standard material like B,K,T, etc, these polynomials are already available in the literature or by the manufacturer, or in the standard whatever is given by the standard laboratory. So what I am going to do is I am simply going to borrow them and use them.

In case I do that, if the thermocouple I have got with me is not exactly like the thermocouple which was used for standardization I might have some errors. So I will come back to this question how to look at these errors little later on, but in principle, I am going to use this table which is given by the manufacturer to measure the temperatures. So with this background let me go back to this slide show and look at some other practical aspects, whatever is possible, within the next few minutes available to us in this lecture.

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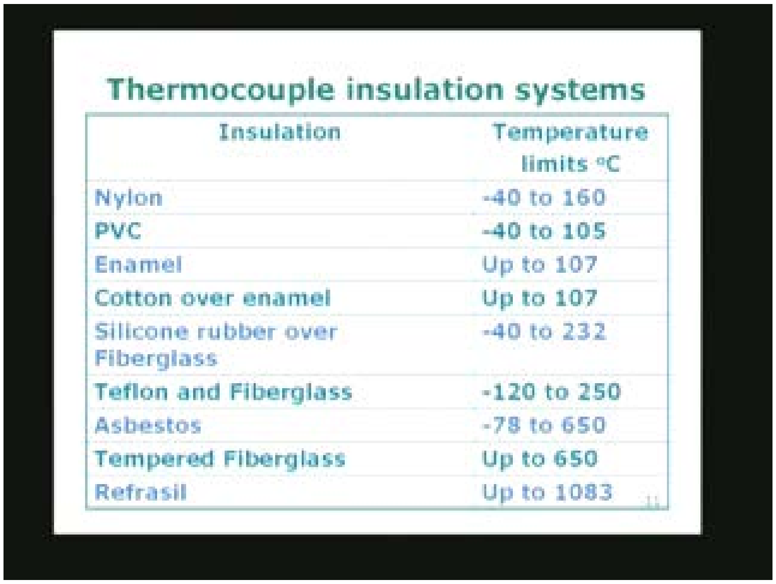

Thermocouple insulation systems

| Insulation | Temperature limits °C |
|---|---|
| Nylon | -40 to 160 |
| PVC | -40 to 105 |
| Enamel | Up to 107 |
| Cotton over enamel | Up to 107 |
| Silicone rubber over Fiberglass | -40 to 232 |
| Teflon and Fiberglass | -120 to 250 |
| Asbestos | -78 to 650 |
| Tempered Fiberglass | Up to 650 |
| Refrasil | Up to 1083 |

The thermocouples, let me just highlight that it contains, as you can see, two wires, and these two wires should not touch each other anywhere, excepting near the junction where the two materials are going to be in intimate contact. If you remember, the circuits which you were drawing all the time, there are two junctions and the wires are shown separated.

Actually, the wires are not separated in practice. They are going to go through a cable. That means, they are going to be like any other electrical wire which you see in the market. So the two wires, the positive and the negative, are going to be joined together only at the junction, and after that, it is going to be individually insulated, electrically insulated, using a sheath material, and in fact, we have already referred to the color coding for the sheath material, and usually these two wires are again put inside a sheath which is going to cover the entire thing.

Normally, the sheet which covers the two cables together will be brown colored, either plastic or some other material which is going to be the sheath material. That means, we need some electrically resisting covering around the two wires, and the covering material can be different types of materials, and these insulation materials are given in this table. So nylon, it can be used between minus 40 and 1610 degrees. That is, relatively low temperatures.

PVC, polyvinyl chlorides, minus 40 to 105, then we have enamel up to about 107 degrees, cotton over enamel, now you have enamel covering the wire and over that there is a cotton covering, up to 107. You can have silicon rubber over fiberglass minus 40 to 232. You see that as you go down here the temperature range is increasing. I am going to materials which are useful for higher and higher temperature. Teflon and fiberglass, minus 120 to 250. Asbestos, we can go up to 650, tempered fiberglass I can go up to 650, and this Refrasil is a manufactured item which is the trade name for that material which may contains silica and other materials in it, this can go up to about 1000 degrees or more. So, these are the normal insulating materials which are used, and in case we don’t have any material which can be used for the insulation we may have to use the two wires.

Two wires have to be run separately away from each other by using, for example, like in the electrical heaters, the heating elements. We have porcelain and beads. We can use, similarly, porcelain tubes or porcelain bead, which is going to do that. So we come to the question, ceramic protecting tube materials and this is what we were talking about just now.

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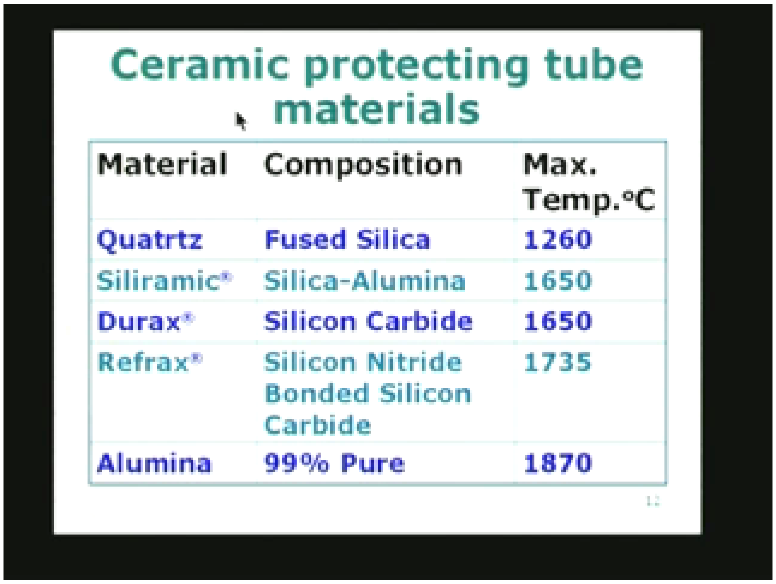

## Ceramic protecting tube materials

| Material | Composition | Max. Temp.°C |
|---|---|---|
| Quatrtz | Fused Silica | 1260 |
| Siliramic® | Silica-Alumina | 1650 |
| Durax® | Silicon Carbide | 1650 |
| Refrax® | Silicon Nitride Bonded Silicon Carbide | 1735 |
| Alumina | 99% Pure | 1870 |

We use, instead of covering in the form a sheath, you can use a tube. I can use the quartz tube. I can have a quartz tube with two holes in the tube through which the two wires can be run. It is nothing but quartz-fused silica composition. I can go up to 1260 siliramic silicon and alumina combination. There is the registered trademark 1650, and you can see that alumina, pure alumina, 99% pure can go up to about 1870. There is, of course, silicon nitride with silicon carbide, and so on. These are materials which are used for very high temperatures. These are actually ceramic protecting tubes.

Sometimes even metal tubes can be used with the ceramic in between the metal and the wire which we want to insulate. The next question I am going to ask is how are we going to make this junction between the two materials, the two wires? These are all the practical aspect we will quickly go through. If one wants to learn all these things, one has to go to the references which describe in great details these procedures, and so on. And we don’t have time to do that in this set of lectures we are giving. There are lots of things to be talked about, and we will just go over quickly the thermocouple junction types.

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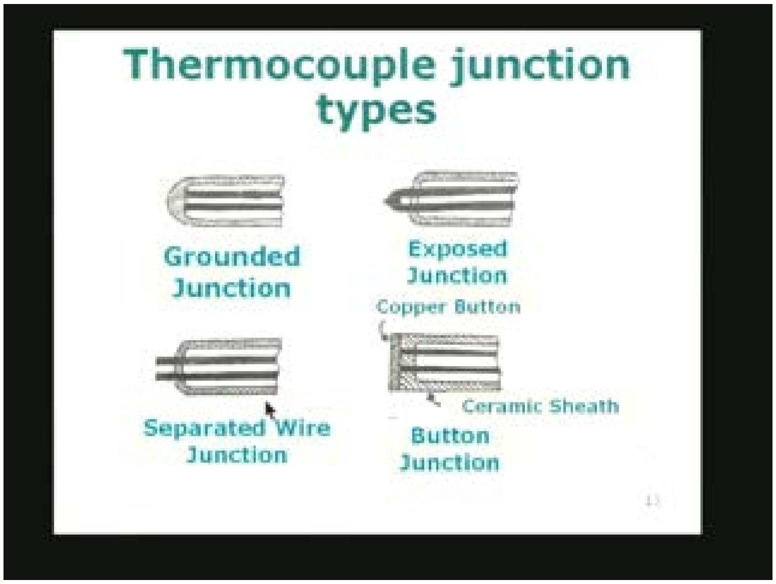

Thermocouple junction types

Grounded Junction

Exposed Junction

Separated Wire Junction

Button Junction

We can have grounded junction. This is the sheath material which is made up of the material metal like stainless steel or Nickel or some such material, and I have attached the two wires directly on to the sheath material at the bottom, and the junction between the two materials is from between this and this by the sheath which is going to be in contact with the two metals, that is why it is called the grounded junction. We can also have an exposed junction. The two wires are brought out of the sheath and they are welded like this. There is a butt weld, and this is an exposed junction.

The advantage with the exposed junction is that it has a quicker time response for any changes in the temperature. It responds more quickly as compared to the grounded junction, because it is in direct contact with the material whose temperature I want to measure. You can also have what is called as separated wire junction, which is very common in metallurgical practice where you want to measure temperature of molten metal. The molten metal itself forms the junction, so you have the K - type thermocouple, let us see, you have the k chromel and alumel coming out of the sheath, and these two are not connected directly. There is no welding or joint between the two and the molten material which is going to be surrounding this automatically provides the contact between the two junctions, two materials, and it forms the junction. So, separated wire junction is being formed by the metal or the molten metal in which it is going to be immersed.

You can also have what is called a button junction. So we have a copper button, button is like a, it’s like a button. It is a cylindrical small disc to which the two wires are attached and of course, there is a ceramic sheath so that there is no physical contact, electrical contact, between the two wires, this wire and these two wires, excepting through this copper button, and in order to understand why these junctions things junctions work in practice we have to learn a few more things which we will do later on.

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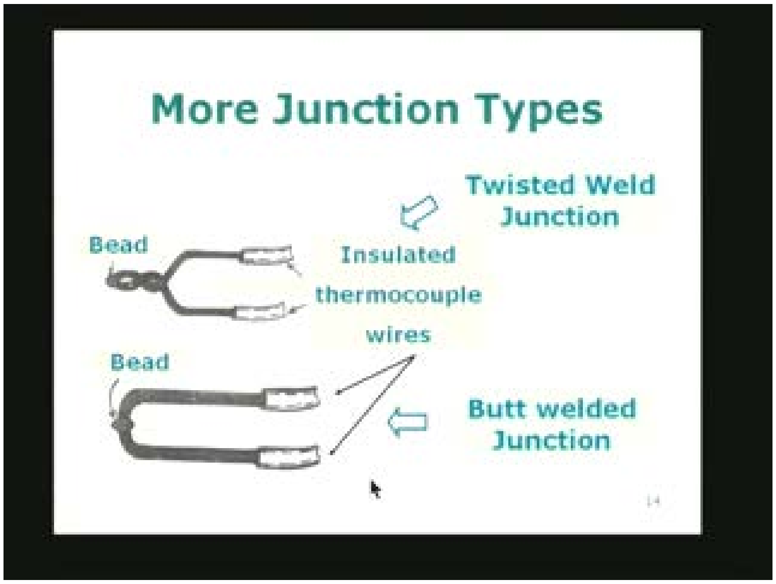

## More Junction Types

Twisted Weld Junction

Bead

Insulated thermocouple wires

Bead

Butt welded Junction

More junction types, I have two more which are very useful. One is called twisted weld junction. In normal practice, you remove the sheath up to a certain length of the wire. This is the positive, and this is the negative, let us say. Then you twist the two things together and make a bead here by welding the two materials to form a contact you can also do a butt-welded junction where the two wires are brought like this, and right there that is the butt weld, and in fact, the welding can be done by several methods, or you can even use soldering as a method for a making beads, so what is normally done is we charge the capacitor to a high voltage, and then the two terminals of the capacitor are connected to the bead here and you close the switch, immediately the charge in the capacitor is going to be discharged through this material and will heat the material locally and it will form a nice weld, and usually, you want to form a nice spherical bead of the junction, and it should be as small as possible, because it depends on of course the wire diameter and so on.

If you use very small diameter wires you can make very small beads which will be sub-millimeter diameter, and the smaller the diameter of the bead, the higher the faster the response of the thermocouple when you want to use it to measure temperatures which are varying with respect to time. Another possible way of making a thermocouple is to use what is called bayonet or the pencil type.

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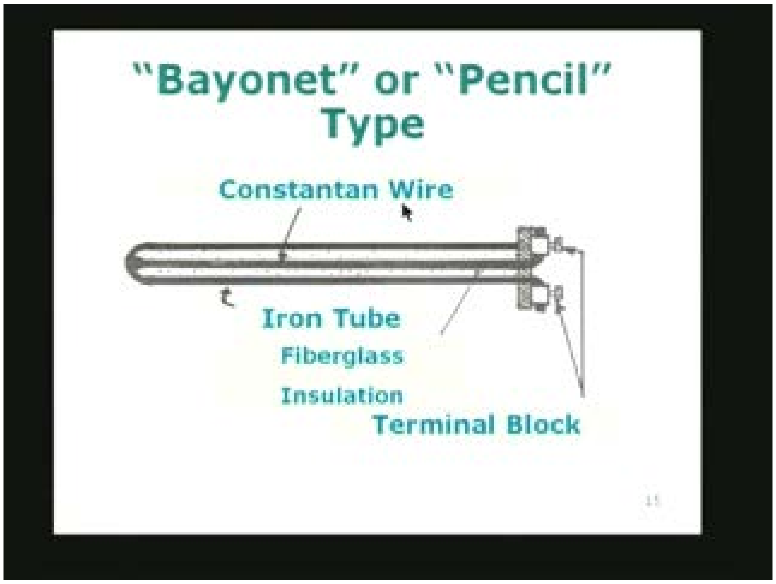
“Bayonet” or “Pencil” Type

In this case, I am using an iron constantan thermocouple which is J type. The tube is made of iron, the constantan wire is right in the middle of the tube and it is attached to the bottom of the tube here. So the junction is here and in between the constantan wire, and the outer iron tube has got some fiberglass insulation which prevents any contact within the two, and these two, the constantan and the iron, are brought to the terminal block, and from the terminal block I can take a connection to the voltage-measuring device. So we have a bayonet or pencil type device. The temperature surrounding this area is measured by introducing the bayonet or the pencil through the side of the place, for example, if you want to measure the temperature in a big duct, or some such thing, you can introduce it through a hole in the side, and then you will be measuring the temperature of the fluid which is flowing inside the duct. So, with the practical aspects in mind, now let us go back and see how a thermocouple circuit is to be made.

We will also find what are the principles involved in this so that you are able to measure the temperature which you intend to measure as accurately as possible without committing any blunder in the process. So let me just go through the simplest form of thermocouple circuit which is shown here.

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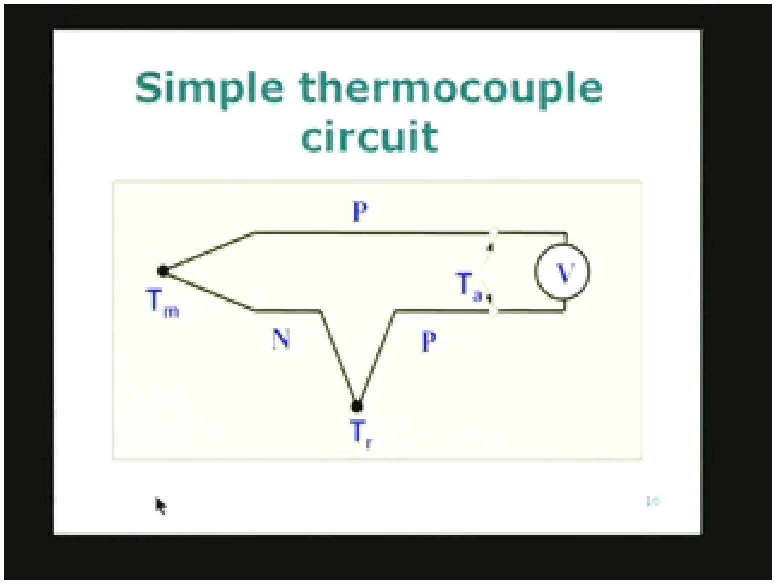

## Simple thermocouple circuit

I have the positive wire which I call as P. I got the negative wire and I got the measuring junction that is there. I have made a bead here and the negative material is now brought here. There is a bead with the positive material. So you see that the voltage is measured between the positive and the positive.

There are two junctions, the measuring junction, P N, and the reference junction is the N P. If you go in this direction, or in one direction or the other, you will see that you are going from P to N, from N to P, and then I have got two terminals where the P material, or the positive material has come and it is attached. These two terminal are the terminals of the voltmeter. Because the voltmeter has to be connected to measure the voltage across the two thermocouple wires, and, therefore, you got two terminals, and chances are the wire which is connecting inside is not necessarily either P or N material, chances are it is a different material.

For example, I may have copper here. This is copper, so immediately you see that if you have positive material here and copper and positive material here there are two junctions formed between P and copper or P, and some third material. And again, another junction P, and third material, one in this direction, the other one in this direction. If the two terminals are at the same temperature we will come back to this question little later. If the two terminals are at the same temperature this is not going to affect the measurement. If the two terminals are not at the same temperature, we have to worry about it.

Normally, what is to be done is these two terminals are placed on what is called a junction box, and the junction box consists of a material of high thermal electric material like a block of aluminum or block of copper. On that, you have two insulated legs and to each leg you can connect the wires, and the insulated legs will prevent contact or shorting between the two terminals, but it will be in contact with the material of high thermal conductivity which can be maintained, if necessary, by cooling it or by placing it in contact with some fluid whose temperature is constant. That means I have to maintain the temperature with the two terminals at the same value. If you do that, you will be able to whatever thermoelectric voltage you measure between these junctions and these junctions by the voltmeter that you can plug into the formula which we gave earlier. If you are using the K - type thermocouple you use that formula. If it is some other type you go to get the right kind of polynomial and substitute and you get the value of the temperature. You use the inverse relationship.

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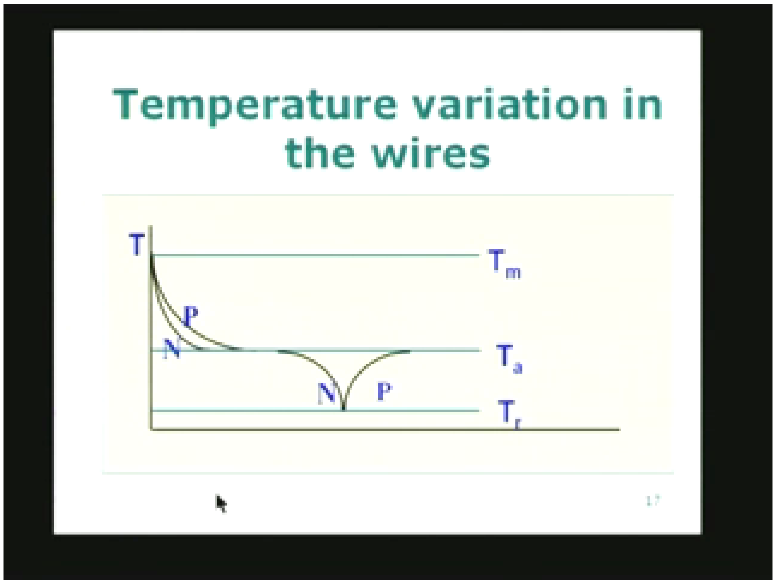

Temperature variation in the wires

Now, let us look at the details of what is happening in the wires. What I am doing is I am looking at the temperature variation on the wires in this circuit. There are several wires, P wire here, the N wire here, (Refer Slide Time 52:05 ) another P wire here, and may be some other material, copper, whatever. So I am going to look at the temperature variation on these wires, because, if you remember, the thermoelectric phenomenon is due to the temperature variation all along the wires which are used for making the thermocouple.

We have the Peltier effect which is localized in the junction, we have Thomson effect which is going to take place all along the wires which are connecting the different parts of the circuit. So, if there are three temperatures effectively, $T_m$ then $T_r$ and $T_a$, these are three temperature levels in this particular problem. So, what I am going to do is to look at the temperature variation along each wire. Suppose I take the wire P here at this point, temperature is $T_a$, at this point temperature is $T_m$, therefore, temperature is reduced along here from $T_m$ to $T_a$, and it probably will do according to this. It varies like this and comes to $T_a$.

Similarly, you take the N type thermo N type material it is going from $T_m$, and then it’s going to $T_r$, but somewhere here it may be at the ambient temperature, so what you expect is that it also goes to $T_a$ and then further as you go near the reference junction it is going to the ice point. So, ice point that means it is going to be at this temperature. So the temperature in the P wire is going like this and becoming $T_a$. The N wire is going like this, becoming $T_a$, and then again it goes down to the ice point, and at the ice point the other material is the P material which is going to go from the ice point to the ambient temperature or $T_a$ and that is what I have.

Actually, the distance between the junction P and the $T_m$ and this and this junction and the voltmeter may be quite large. For example, if I am using a very thin wire of diameter say point 1 point 5 millimeter, let us say, the length of the wire may be 1 meter, in which case is very very far off. The length of the wire is very large compared to the cross-sectional diameter of the wire, so the point is this temperature variation is localized close to the high temperature zone, this is close to the low temperature zone. Therefore, this portion I am showing here which is at the room temperature, or the ambient temperature, is a very long length.

Therefore, if you look at the thermoelectric phenomena which is taking place we can say that thermoelectric phenomena is taking place close to the junction here and close to the junction here because the Thomson emf is generated only when there is a variation in the temperature along the wire. Therefore, you can say that the Thomson effect, of course the Peltier effect is localized at this junction.

Therefore, we have the fact, that is, these wires are very long and the temperature variation is localized near the junction, we can say that the thermoelectric effect or thermoelectric phenomena which is taking place is localized to the junction area and therefore, we need not waste the good material P material or N material by having very long wires made up of thermocouple wires.

Therefore, normally what is done in practice is to replace or to go from very close to the junction, may be we can take a few centimeters or few may be few tens of centimeters of the thermocouple wire and then from there onwards we can use a lead wire which need not be the thermocouple wire which is usually very expensive.

So, what we will do in the next lecture is to look at this aspect, and then we will take up a few examples how thermocouple circuits are analyzed, and then we will able to come to the question of the errors in thermometry using thermoelectric thermometers or thermocouples, and we look at how to estimate these errors, how to look at these errors, or model these errors in thermal, in terms of heat transfer models, and how to calculate these errors. This will be the done in the next one or two lectures. Thank you.