

Something about temperature for everybody! Something to remember, something just to read and forget for somebody !!

1.0 HEAT AND TEMPERATURE IN A HISTORICAL PERSPECTIVE

As far as history goes back, man has always been aware of concepts like heat and temperature.

What is heat? This question has been raised many times through the history of science and found many very different answers.

As many physical and chemical phenomena are accompanied by generation of heat, man very early considered heat to be one of the most important driving forces in nature. As late as in 1800, heat was considered to be some kind of a refined ethereal creature, a kind of fire material without weight, but which nevertheless was able to penetrate all materials. Actually, this definition fitted well with the phenomena that could be observed. Thus, the presence and departure of this special heat substance or fire material was believed to be able to put a material in different heat conditions and at the same time assume new chemical characteristics.

After year 1800, when man became aware of the composition of materials in elementary particles and molecules, it became known at the same time that heat was an expression for energy and the degree of heat an expression for energy level.

1.1 Measurement of temperature. Historical résumé.

Galileo Galilei (1592):

Galilei is normally known to be the first scientist to be able to measure temperature and has therefore been credited with the invention of the thermometer.

Thus, one of his pupils, *Vincenzo Viviani*, in "Life of Galileo" says:

"....that about the time Galileo took the Chair of Mathematics in Padua at the end of 1592, he invented the thermometer, a glass containing air and water....."

A letter from Francesco Sagredo to Galileo, dated May 9, 1626, reads:

"The instrument for measuring heat, which you invented, I have made several convenient styles, so that differences in

temperature between one place and another can be determined."

The invention was very important, as it became possible for the first time to exchange scientific results, where temperature measurements were included and at the same time to reproduce and compare experiments independently of geography.

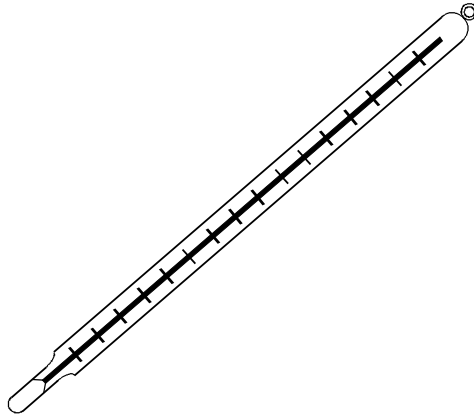
1.2 Other important names and dates

Ferdinand II, Grand Duke of Tuscany (1654)

Made the first thermometer filled with alcohol, and then hermetically sealed the fluid within the bulb and stem. It was the first thermometer made to be independent of pressure, and very much like the glass thermometer we still are using today.

Robert Hook (1664)

Indicated the zero point, as the level of the liquid column, with the thermometer placed in a mix of ice and water.



Christian Huygens (1665)

is quoted as follows:

"It would be well to have a universal and determinate standard for heat and cold, securing a definite proportion between the capacity of the bulb and the tube, and then taking for the commencement

the degree of cold at which water begins to freeze, or better the temperature of boiling water."

Robert boyle (1665)

In a letter dated January 2, 1665, he wrote:

"We are greatly at a loss for a standard! Not only the several differences of this quantity (Temperature) have no names assigned to them, but our sense of feeling cannot therein be depended upon; and thermometers are such very variable things that it seems morally impossible for them to settle such a measure of coldness as we have of time, distance, weight"

Carlo Renaldini (1694)

Suggests melting point of ice and boiling point of water to be used as fix points, to form basis for a temperature scale.

Fahrenheit (1706)

Defines the zero point as a temperature for a mixture of ice, water and sal ammoniac. He fixes the boiling point of water at 212°F, which results in the melting point for ice to be fixed at 32°.

We have now 3 fix points to define the temperature scale!

Anders Celsius (1742)

Divides up the temperature scale between melting point of ice and boiling point of water in hundredths.

The Celsius Scale!

ABOUT 1750 THE UNDERSTANDING OF HEAT IS CHANGED FROM BEING THE PRESENCE OF A SPECIAL HEAT SUBSTANCE OR FIRE MATERIAL, TO A THEORY OF MOLECULAR MOVEMENT (ENERGY REFLECTION).

2.0 Temperature as an energy consideration

The temperature [T] in a material is an expression and a measure for the moving energy of the molecular.

The temperature [T] can furthermore be recognised as being completely independent of size and mass of the material.

Thus the temperature of a material may be described as a size of a condition.

From this will also appear that the absolute temperature zero point is achieved, when the energy level is exactly zero.

$$E_k = C \cdot T$$

E_k = Movement energy, kinetic energy

C = A material constant

T = Temperature measured in Kelvin

In practice, this kinetic energy can very easily be observed. When heating water, water often boils over, which in fact means that the water begins to take up more space. The expansion of the water is an expression for a high energy level, which causes the water molecular to take up more space due to the heavy vibrations.

If the vibrations become even heavier, the molecular will start leaving the water surface and you say that the water is boiling.

When water is boiling, a phase change has started. The water passes from floating form into gas form, or vapour.

The triple point of a material is characterised exactly by the temperature at which all three phases are present simultaneously, i.e. solid, fluid and vapour. This phenomenon is very important for the determination of the temperature scale in practice. See paragraph 4.1

2.1 The Thermodynamic temperature Scale, The Kelvin scale.

No matter which scale is used, all measured temperatures can be referred back to "The Thermodynamic Kelvin Scale".

In theory, the scale is based on [an ideal reversible Carnot cycle], which is the consequence of the second principal sentence of the thermodynamic:

Heat is never moving by itself from a body with low temperature to a body with higher temperature.

It can be proved that the thermal efficiency η , is [independent of the working substance and depends only on the temperature between which it operates].

$$\eta = \frac{Q_2 - Q_1}{Q_2} = \frac{T_2 - T_1}{T_2}$$

Where:

Q_2 = The heat absorbed from a reservoir at temperature T_2

Q_1 = The heat rejected to a reservoir at a lower temperature T_1

By that can also be defined that:

$$\frac{Q_1}{Q_2} = \frac{T_2}{T_1}$$

One Kelvin is equal to a 273.16 part of the thermodynamic temperature of the triple point of water (paragraph 6).

3.0 The International Practical Temperature Scale.

If it was possible to produce an instrument with sufficient accuracy and resolution for direct measurement of the energy level at a certain temperature, this would be regarded as the ideal thermometer. With the existing requirements from science and industry, this is however not yet possible, and it is therefore necessary to agree internationally on how a practical temperature scale should be established and last but not least, with which instruments a given temperature should be measured.

In 1927, the first practical temperature scale was defined and became generally recognised all over the world. The scale was, like today, based on a number of fix points. A fix point is a physical heating source, which at a defined temperature, has the characteristic of being 100% temperature stable (pls. also see chapter xxx). To be able to determine a temperature between two fix points, it is also important to agree on which interpolation instrument as well as on which procedure to use for calculations between the points.

Over the years, this scale from 1927 has been changed several times, and it became possible to define the fix point temperature itself with higher accuracy. Moreover, new generations of thermometers with higher accuracy, which could also be used as interpolation instruments, were developed.

As all measurements of temperature on all levels are indirect measurements, it will only be possible to measure the influence of the temperature on the thermometer and not on the temperature itself.

If, for instance, you would measure the temperature in a cup of hot coffee, naturally you put your thermometer into the coffee. The coffee will now heat up the thermometer and a temperature can be read on the scale. However, as the coffee has to use some of its heat energy to heat up the thermometer, it is obvious that this has caused a cooling of the coffee. Consequently, what you read on the thermometer scale is not the temperature that you wanted to measure, but the temperature effect of the thermometer on the temperature of the coffee.

The change of the temperature scale from 1927 to 1990, and the definition of the most important fix points and their temperatures in [°C]				
	ITS-27	IPTS-48	IPTS-68	ITS-90
ARGON (TP)			-189.352	-189.3442
OXYGEN (BP)	-182.97	-182.97	-182.962	
MERCURY (TP)				-38.8344
WATER (FP)	0	0	(0)	
WATER (TP)		0.01	0.01	0.01
GALLIUM (MP)				29.7646
WATER (BP)	100	100	100	
INDIUM (FP)			(156.634)	156.5985
TIN (FP)			231.9681	231.928
ZINC (FP)		(419.505)	419.58	419.527
SULPHUR (BP)	444.60	444.60	(444.674)	
ALUMINIUM (FP)		(660.1)	(660.46)	660.323
SILVER (FP)	960.5	960.8	961.93	961.78
GOLD (FP)	1063	1063	1064.43	1064.18
COPPER (FP)			(1084.88)	1084.62

- TP - Triple point
- FP - Freezing point
- BP - Boiling point
- MP - Melting point

The temperatures in brackets are secondary fix points.

The temperatures indicated in the table are absolute temperatures, i.e. the temperature of a specific fix point is by definition exact and internationally agreed. As an example, the freezing point of aluminium is indicated as 660.323°C, which means that this temperature has been accepted as the freezing point of aluminium, not with less decimals and not with more.

From longimetry we also know of such decisions, and a typical example is the conversion between an English inch and a centimetre. Here an inch is by definition equal to 2.54 cm.

3.1 The interpolation instrument, the SPRT sensor

Now, having agreed upon a number of fix points from almost absolute zero (K) more than 1000°C, it is just as important to define, with which instrument

the temperature between these points should be determined, meaning that you have to use a defined interpolation instrument.

It is commonly accepted that this instrument is a temperature sensor with the general designation "SPRT" (Standard Platinum Resistance Thermometer). This resistance thermometer differs in several important points from the platinum sensors which are known from typical measurement and surveillance applications within industry.

First of all, the platinum which is used as measuring resistor is extremely well defined as to purity. Besides, it is of great importance that the coil which represents the resistance itself, is suspended in such a way that the mechanical influence at high temperatures does not result in a strain gauge effect, i.e. that the resistance changes due to bending.

Besides, it is important that the dimensions of the sensor allows fix point calibration. The typical dimensions of an SPRT sensor are approx. 450-500 mm in length and with a diameter of approx. 5 mm.

The resistor itself is connected in accordance with the 4-wire principle, so that only the resistor is measured and not the resistance in the power supply lines

The reason why platinum is used as resistor is that platinum first of all has a very fine linearity of resistance versus temperature. Besides, being a precious metal, platinum has very ideal characteristics in connection with long term thermal stress.

However, in spite of these very fine characteristics, it is nevertheless necessary to protect the resistor coil itself against pollution from the surroundings. Normally, the coil itself is built hermetically tight into a quartz tube filled with a gas consisting of for example argon with approx. 10% oxygen added.

If all above mentioned construction conditions have been observed, it is possible to produce a thermometer which is able to reproduce measurement results within very narrow limits even in connection with measurements executed at high temperatures. A good SPRT sensor may reproduce temperature measurements within $\pm 0.01^{\circ}\text{C}$ over a calibration period of one year, even if it is used often at temperatures of approx. 650°C .

Finally, it is very important, when measuring temperatures with an SPRT sensor, that the mathematical basis on which the linearization is calculated and the method of converting Ohm signals into temperatures are agreed internationally.

4.0 The International Temperature Scale of 1990 (ITS-90)

On January 1, 1990, the temperature scale was changed last time. Therefore, this is the scale to be used for calculations of actual temperature.

The change was especially based on the fact that SPRT sensors on reference level had a stability at high temperatures so good that they could be used as interpolation instruments from almost absolute 0 until the freezing point of silver (Ag(FP)) = 961.78°C. When using the previous scale of IPTS-68, it was necessary to use thermocouple sensors at temperatures higher than 630°C. Because it involved higher uncertainties when using this kind of sensors, it was not possible to determine fix point temperatures as it is today.

But not only was the temperature definition for the different fix point cells changed, also the value of one Ohm and the value of one Volt were changed.

The definition of volt [V]:

The definition of volt is based on the so-called "Josephson effect" (Discovered in 1962).

$$E = \frac{n \cdot f}{K_j}$$

Where: $n = 1$ step in the Josephson effect
 $f =$ Frequency
 $K_j = 483597,9$ ghZ/v (Thr Josephson constant)

Voltage measured as 1.00000000 V before January 1, 1990, must be reported as 0.99999194 V after January, 1990.

Definition of ohm [Ω]:

The definition of ohm is based on the "Quantum Hall Effect" (Discovered in 1980).

$$R_H(i) = \frac{R_K}{i}$$

Where: $R_K = 25812,807 \Omega$ (The Von Klitzing Constant)
 $i =$ Whole number

Resistance measured as 1.00000000 Ω before January 1, 1990, must be reported as 0.99999944 after January 1990.

Luckily enough, it is not necessary for the common user of temperature measuring equipment to know the details of the above, but it may be important to know whether the meter bridge, to which the SPRT sensor is connected, has been calibrated in accordance with the new definitions.

4.1 Calibration of the SPRT sensor, fix point calibration

For practical reasons we shall confine ourselves only to look at the temperature range 0 to 660.323°C and in other cases to refer to the "NIST Technical Note 1265, Guidelines for Realising the International Temperature Scale of 1990 (ITS-90)".

In this temperature range the following fix points are normally used for the calibration itself:

- 1) Triple point of water (TP H₂O), 0.01°C
- 2) Freezing point of tin (FP Sn) 231.928°C
- 3) Freezing point of zinc (FP Zn) 419.527°C
- 4) Freezing point of aluminium (FP Al) 660.323°C

It has been mentioned before that the SPRT sensor has to meet some requirements to be used legally as interpolation instrument.

An acceptable SPRT sensor must fulfil at least one of the two following conditions:

$$\underline{W(29.7646 \text{ }^\circ\text{C}) \geq 1.11807}$$

$$\underline{W(-38.8344 \text{ }^\circ\text{C}) \leq 0.844235}$$

where:

$$W = \frac{R_t}{R_{0.01}} \quad R_t = \text{Resistance at actual temperature}$$

$$R_{0.01} = \text{Resistance at } 0.01^\circ\text{C (TP H}_2\text{O)}$$

The above means then that at least one more fix point should be used to verify the sensor.

Either: The melting point of Gallium (MP Ga, 29.7646°C)

And/or: Triple point of Mercury (TP Hg, -38.8344°C)

On the certificate should always be stated, whether the calibrated sensor meets the above mentioned conditions.

It should be mentioned that normally laboratories always prefer to work with ratio's . As ratio's have no dimensions, they are converted into absolute values by multiplying with a number. In this case the number will be the resistance at $R_{0.01}$.

To work with ratio's means in practice that you can normally disregard the absolute accuracy of an instrument and instead relate the measurement to a standard unit, for example a reference standard. In this case a resistance of approx. 25Ω .

The meter bridge used for the calibration will normally be of a type where the measurement is performed in proportion to a reference resistance, and the measurement accuracy will mainly be dependent on the accuracy of this resistance. The greatest uncertainty contribution will therefore be the linearity on the meter bridge. In connection with fix point calibration, most often meter bridges with a linearity of approx. 0.5 to 1 PPM (parts per million) are used.

An example of the technique:

$$R_x = R_{std} \cdot \left(\frac{R_{x,meas}}{R_{std,meas}} \right)$$

Where:

- R_x = The measurement result, i.e. the value of the unknown resistance
- R_{std} = The certified value of the reference resistance
- $R_{x,meas}$ = The measurement value of R_x , the unknown resistance
- $R_{std,meas}$ = The measurement value of R_{std} , the reference resistance

It should be mentioned that it is of importance to the accuracy of the result to know the approx. value of R_x , so that the reference resistance can be chosen as close to the value of R_x as possible, meaning that the proportion between R_x and R_{std} should be as close to 1 as possible.

4.2

The calibration

The fix point calibration of the SPRT sensor does not in principle differentiate from other calibrations, i.e. in a specific temperature range you will get connected values of reference temperature and output from the sensor.

In this case by using the 4 fix points, from 0.01°C to 660.323°C (mentioned in paragraph 7.0).

Based on a real certificate for calibration of an SPRT sensor of the manufacture Rosemount, Model 162CE, a reference laboratory has measured the following:

$R_{0.01}$	=	25.54777 Ω
$W(231.928 \text{ } ^\circ\text{C})$	=	1.89258929
$W(419.527 \text{ } ^\circ\text{C})$	=	2.56854768
$W(660.323 \text{ } ^\circ\text{C})$	=	3.37544573

These sets of data shall now be used to calculate the curve through the points which will give the minimum mathematical error. In other words, we have to find a mathematical expression or an equation, which, when using the thermometer in practice, will enable us to measure the temperatures between the fix points.

To go into mathematical details around the calculation, would take us too far and we therefore refer to the guidelines of ITS-90 mentioned before. Consequently, only the functions which are valid for the temperature range 0 to 961.78°C will be mentioned. We are talking about two functions, i.e. a reference function and a deviation function.

First we shall take a look on how to calculate an actual temperature when using the calibration data and coefficients that are normally stated on the certificate.

I REFERENCE FUNCTION

Temperature range 273.15 K (0°C) to 1234.93 K (961.78°C):

1)

$$W_r = C_0 + \sum_{i=1}^9 C_1 \left[\frac{T - 754.15}{481} \right]^i$$

T = Temperature in Kelvin

This function is a 9th order function, where the values for C are table values from guidelines for ITS-90.

In this function, T can only be calculated by means of an iterative process, which is why the inverse function is often used:

2)

$$T - 27315 = D_0 + \sum_{i=1}^i D_i \left[\frac{W_r - 264}{164} \right]^i$$

This inverse function has an error which is less than 0.13 mK in proportion to formula 1.

The values for D are also given table values.

II DEVIATION FUNCTION

Temperature range 234.3156 K (-38.8344 °C) to 933.473 K (660.323 °C)

3)

$$\Delta W = a(W - 1) + b(W - 1)^2 + c(W - 1)^3$$

a, b and c are coefficients or calibration constants indicated on the certificate.

4)

$$\Delta W = W - W_r$$

5)

$$W_r = W - \Delta W$$

The final calculation of actual temperature:

Incorporate equation 5 in equation 2 \Rightarrow

$$t_{90} = D_0 + \sum_{i=1}^i D_i \left[\frac{(W - \Delta W) - 2.64}{1.64} \right]$$

As will appear, it is not exactly simple to calculate the temperature of an SPRT sensor, and we are therefore quite a few who were happy not to have these calculations introduced until 1990, when the personal computer was available for everyone around in the world.

Tom M. hansen