Temperature Measurements

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Contents:

- Introduction:

⇒ What is temperature?

⇒ Temperature scales

- Methods for Temperature Measurement

⇒ Thermal expansion thermometer

⇒ Resistance thermometers

⇒ Thermistors

⇒ Thermocouples

- Calibration
- Application (how to measure)

The def. of temperature depends on the *zeroth law of thermodynamics*:

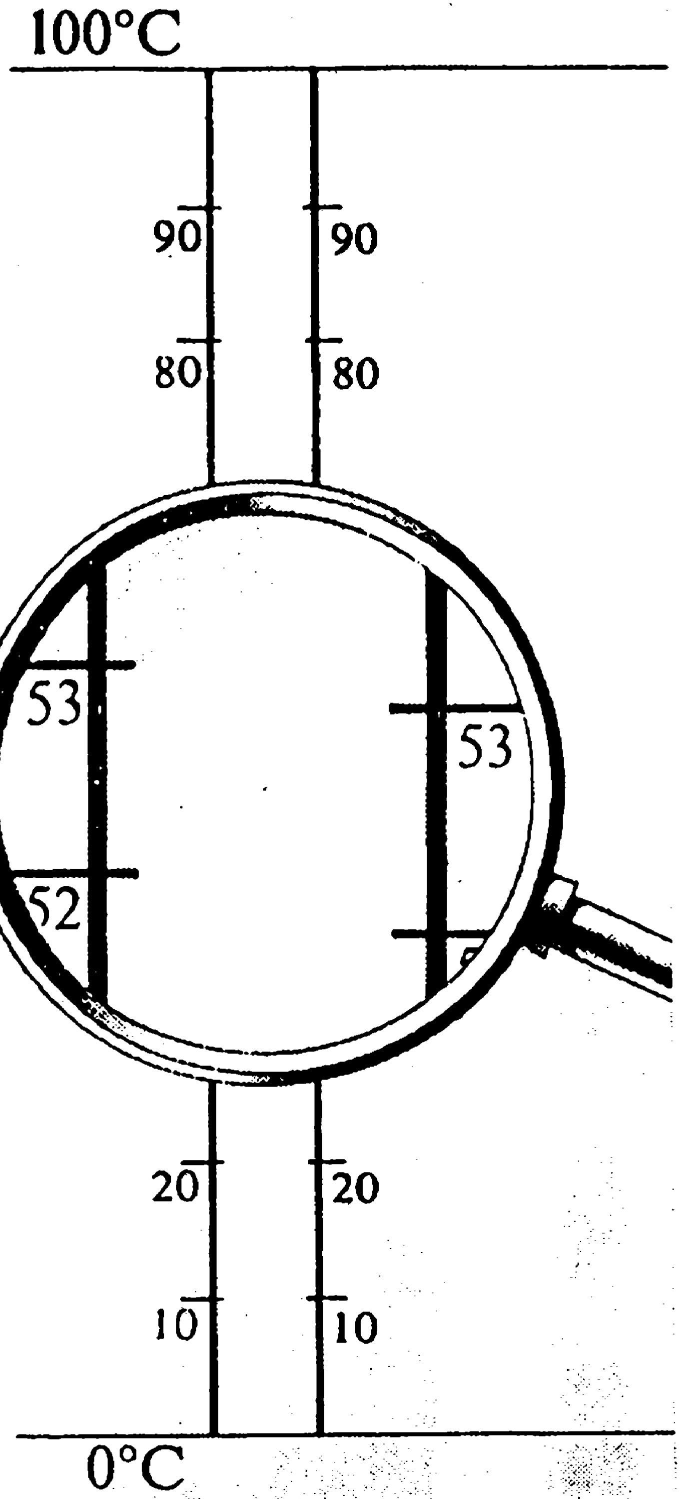
> *Two systems, each in thermal equilibrium with a third system are also in equilibrium with each other.*
> (They are then at the same temperature)

Temperature is the quantity which is the same for two systems if they are in thermal equilibrium.

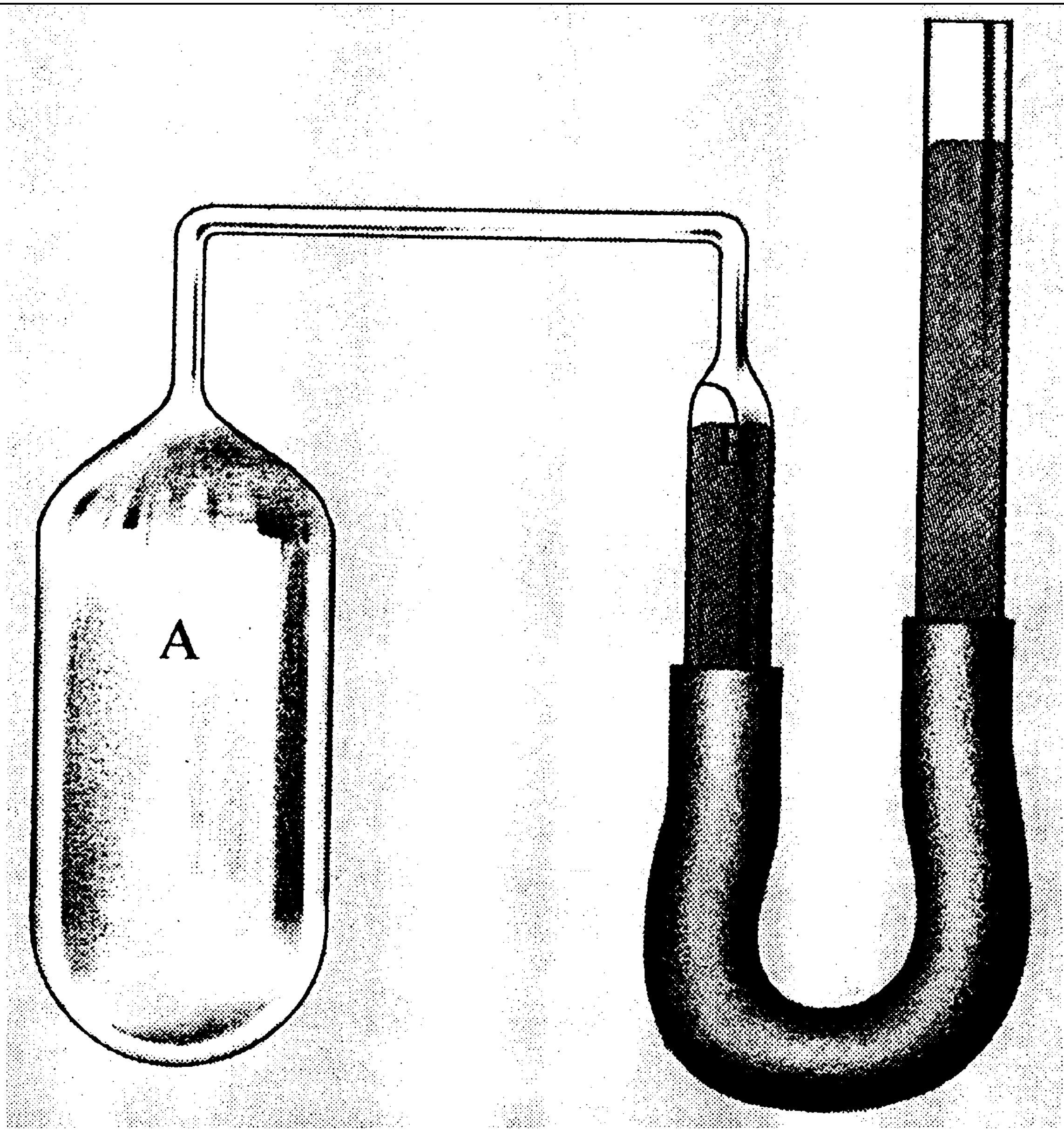
From the kinetic gas theory it is shown that

The average kinetic energy of the molecules = 3kT/2
where k is Boltzmann’s constant

Thus, *temperature is a measure of the thermal motion of the molecules and atoms.*


100°C
90
90
80
80
53
53
52
20
20
10
10
0°C

The gas thermometer



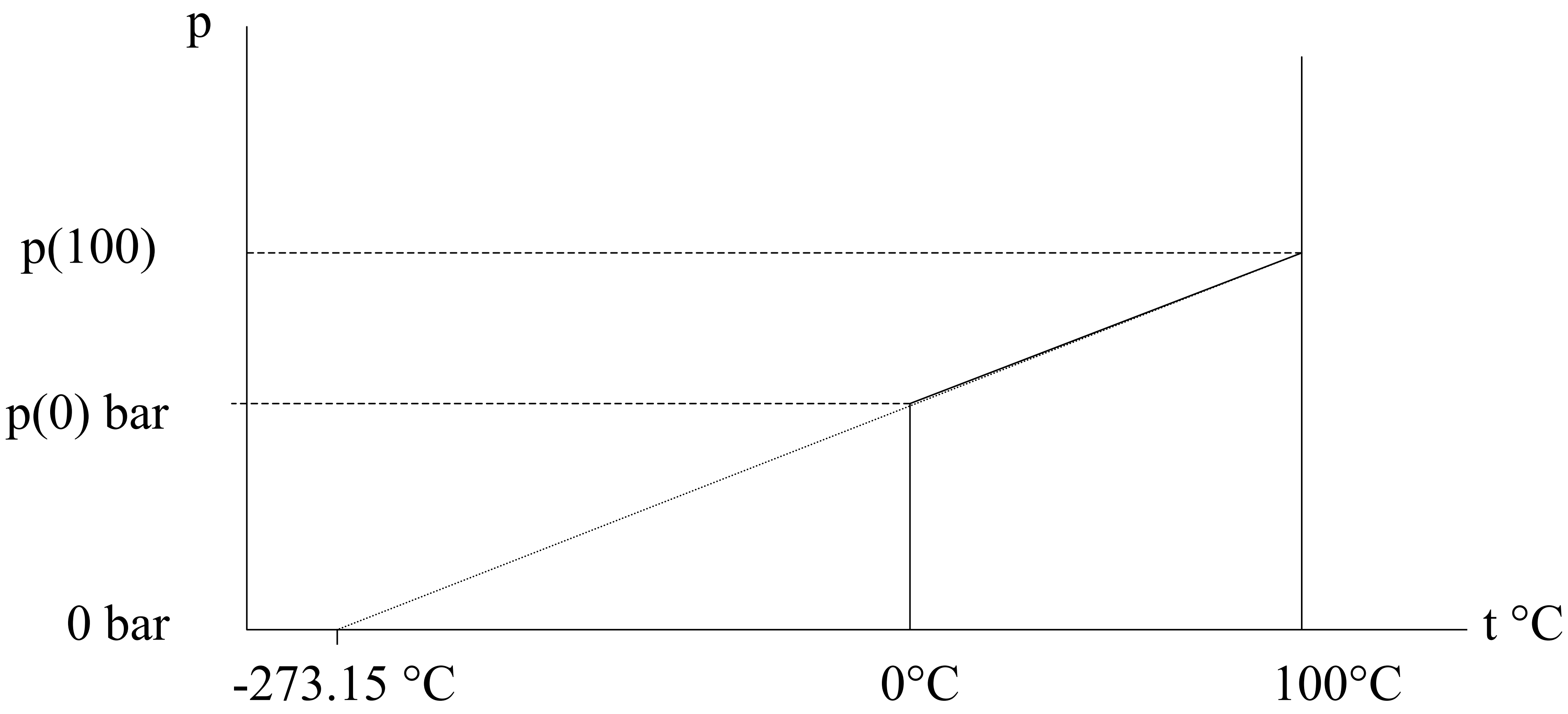
Measurements have shown that the thermodynamic temperature scale is identical to that defined by a gas thermometer with ideal gas.

The gas thermometer is based on the ideal gas law, i.e.

$$p\,V = N \cdot R_m \cdot T$$

In the thermometer there is a known mass of gas (m and R constant). When reading the temperature, a mercury scale is adjusted so that either *p* or *V* is equal to a reference value (i.e. constant). The temperature is thereby directly proportional to V (or p).

As (T=const·p) there must be a *zero level for temperature*. By measuring the pressures at 0°C and 100°C and extrapolating to *p*=0 a value for the absolute zero is attained.



International Temperature Scale (ITS-90)

From the gas thermometer the temperature of a number of well defined states have been *defined*. These states are used as *fix points* for a practical temperature scale (ITS-90).

In total, 17 fix points are defined between -270°C and 1084°C in the latest revision, ITS-90. In between the fix points temperature is defined by the Platinum resistance thermometer according to certain functions.

At temperatures above the melting point of silver (961.78°C) the temperature is defined by two fix points (Au, Cu meltp.) and the Planck radiation law.

International Temperature Scale, ITS-90

Reference Temperatures

Hydrogen triple point	13.8033 K	-259.3467 °C
Hydrogen vapour pressure (near 33 kPa)	~17 K	-256.15 °C
Hydrogen vapour pressure (near 101 kPa)	~20.3 K	-252.85 °C
Neon triple point	24.5561 K	-248.5939 °C
Oxygen triple point	54.3584 K	-218.7916 °C
Argon triple point	83.8058 K	-189.3442 °C
Mercury triple point	234.3156 K	-38.8344 °C
Water triple point	273.16 K	0.01 °C
Gallium melting point	302.9146 K	29.7646 °C
Indium freezing point	429.7485 K	156.5985 °C
Tin freezing point	505.078 K	231.928 °C
Zinc freezing point	692.677 K	419.527 °C
Aluminum freezing point	933.473 K	660.323 °C
Silver freezing point	1234.93 K	961.78 °C
Gold freezing point	1337.33 K	1064.18 °C
Copper freezing point	1357.77 K	1084.62 °C

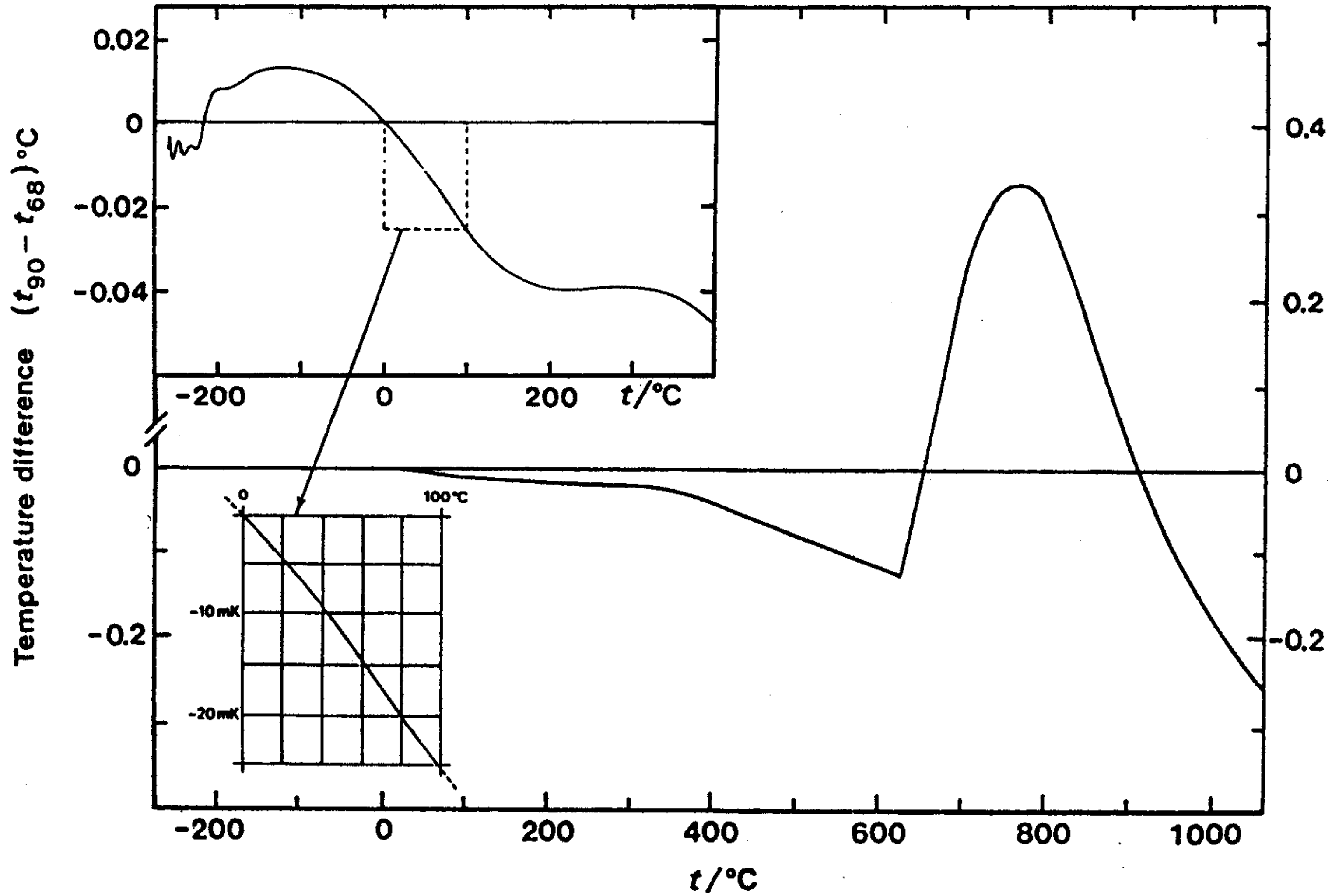
Triple point

Liquid, solid and gas of a single fluid in equilibrium.

Triple point of water 273.16 K the only point necessary to define the Kelvin scale

Boiling point of water at atmospheric pressure according to ITS-90:
99.975°C

Difference between ITS-90 and IPTS-68



Avvikelsen mellan ITS-90 och IPTS-68

På baksidan av detta blad redovisas
skillnaderna i siffror.

Other temperature scales:

- Celsius : $°C = K - 273.15$
- Fahrenheit $°F = 9/5 \cdot °C + 32$
- Rankine $°R = 9/5 \cdot K$

Other system properties than gas volume may be used for temperature measurements:

- Thermal expansion, e.g. mercury thermometer
- Vapor pressure / change of state
- Electric resistance, Pt100, thermistor
- Seebeck-effect (thermo-EMK), thermocouple
- Radiation intensity/”color”, pyrometer, IR-camera
- Color Liquid crystals

Thermal expansion thermometer:

Solid: The difference in thermal expansion between different solid materials is used to give an indication of the temperature.

Often used for thermostats

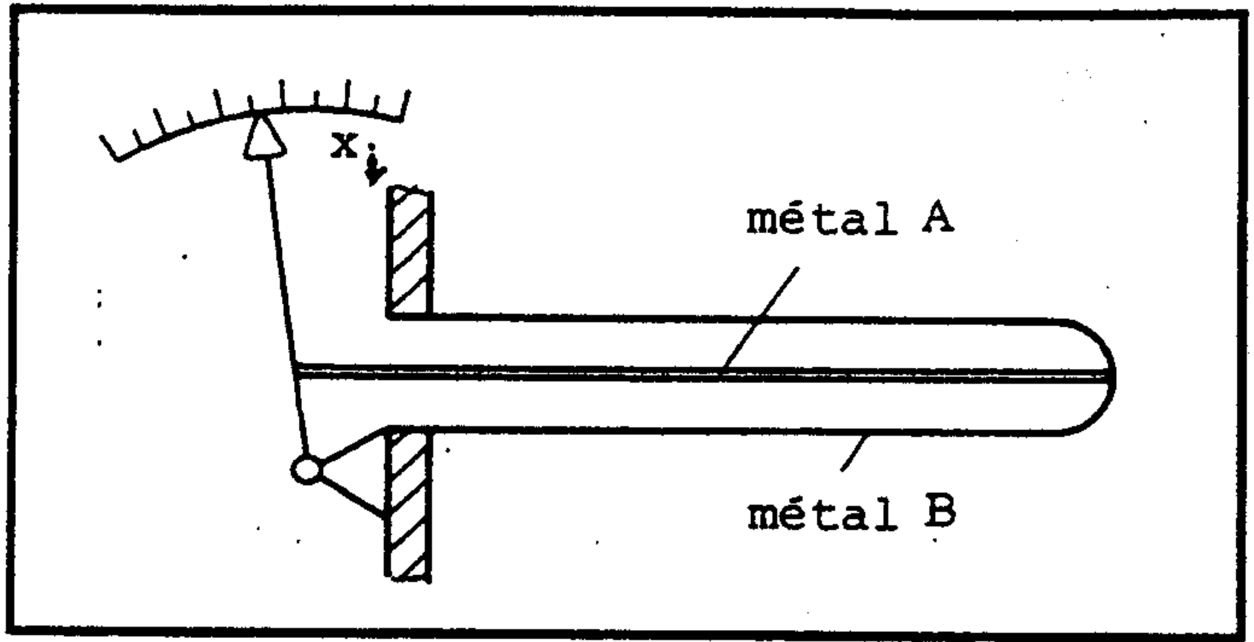
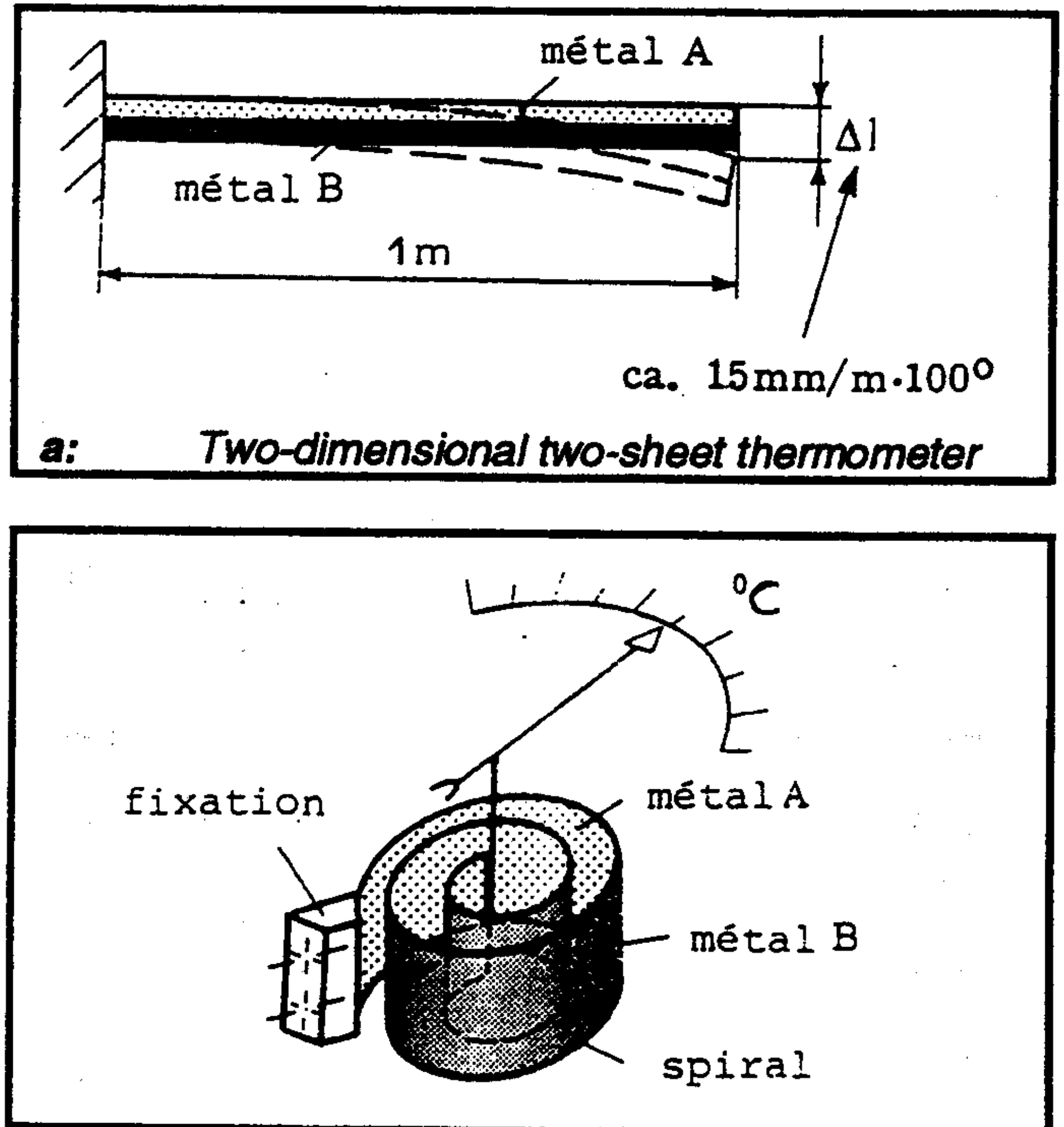


Fig. 10.3: *Thermometer expansion [Spinnler, 1982, p. 18.2]*



a: *Two-dimensional two-sheet thermometer*

b: *Spiral two-sheet thermometer*

Fig. 10.4: *Example of two two-sheet thermometers [Spinnler, 1982, p. 18.2]*

Thermal expansion thermometer:

Liquid expansion: Liquid reservoir is allowed to expand into capillary tube.

Advantages:

- Simple, reliable
- Not easily influenced by the surroundings
- Small risk of changes due to aging

Drawbacks:

- Limited resolution (?)
- Difficult to connect to automatic data acquisition system
- Relatively large bulb, thereby slow response and difficult to apply in small scale.

Thermal expansion thermometer:

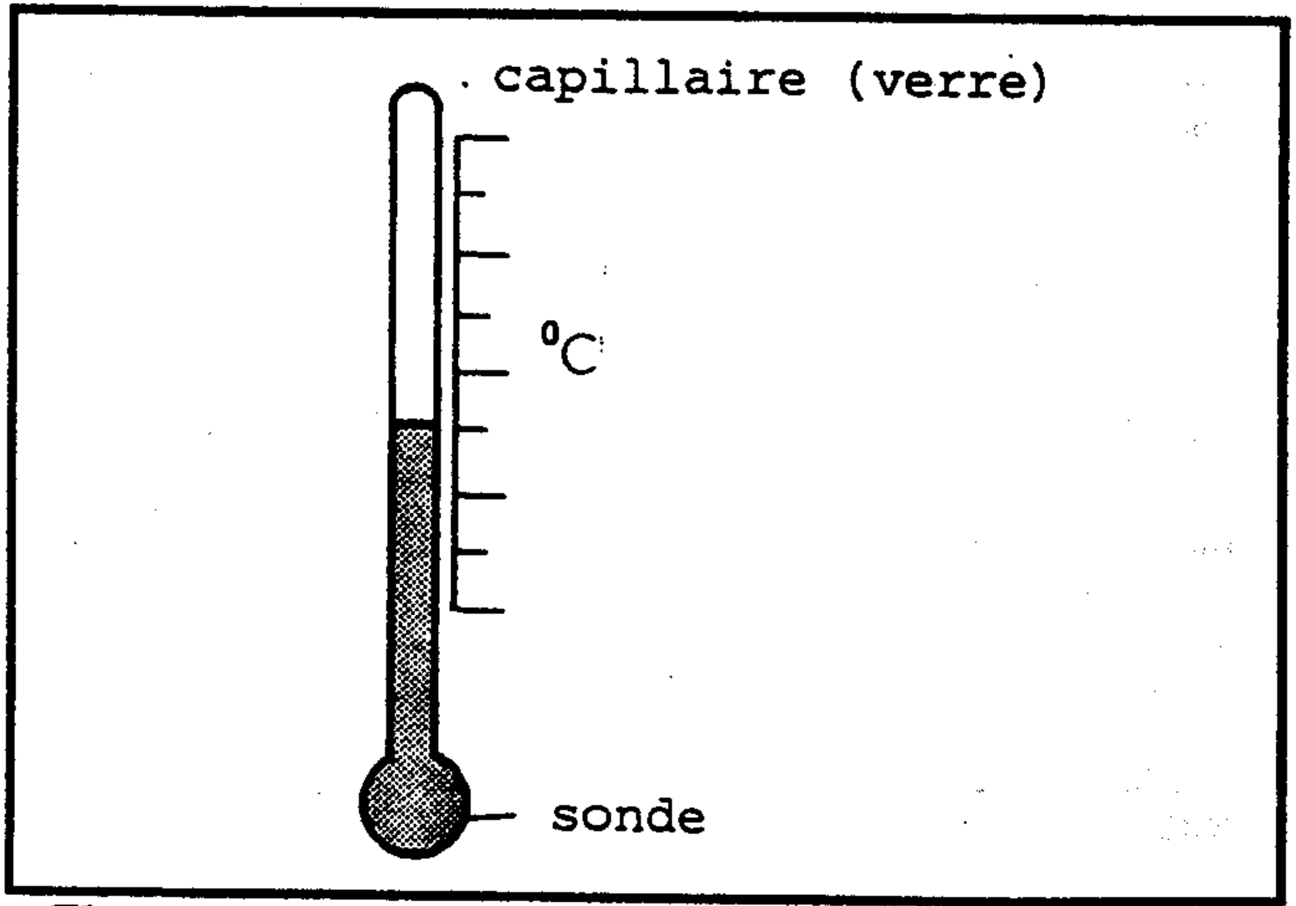


Fig. 10.5a: *Liquid glass thermometer [Spinnler, 1982, p. 18.3]*

Special type of liquid thermometer:

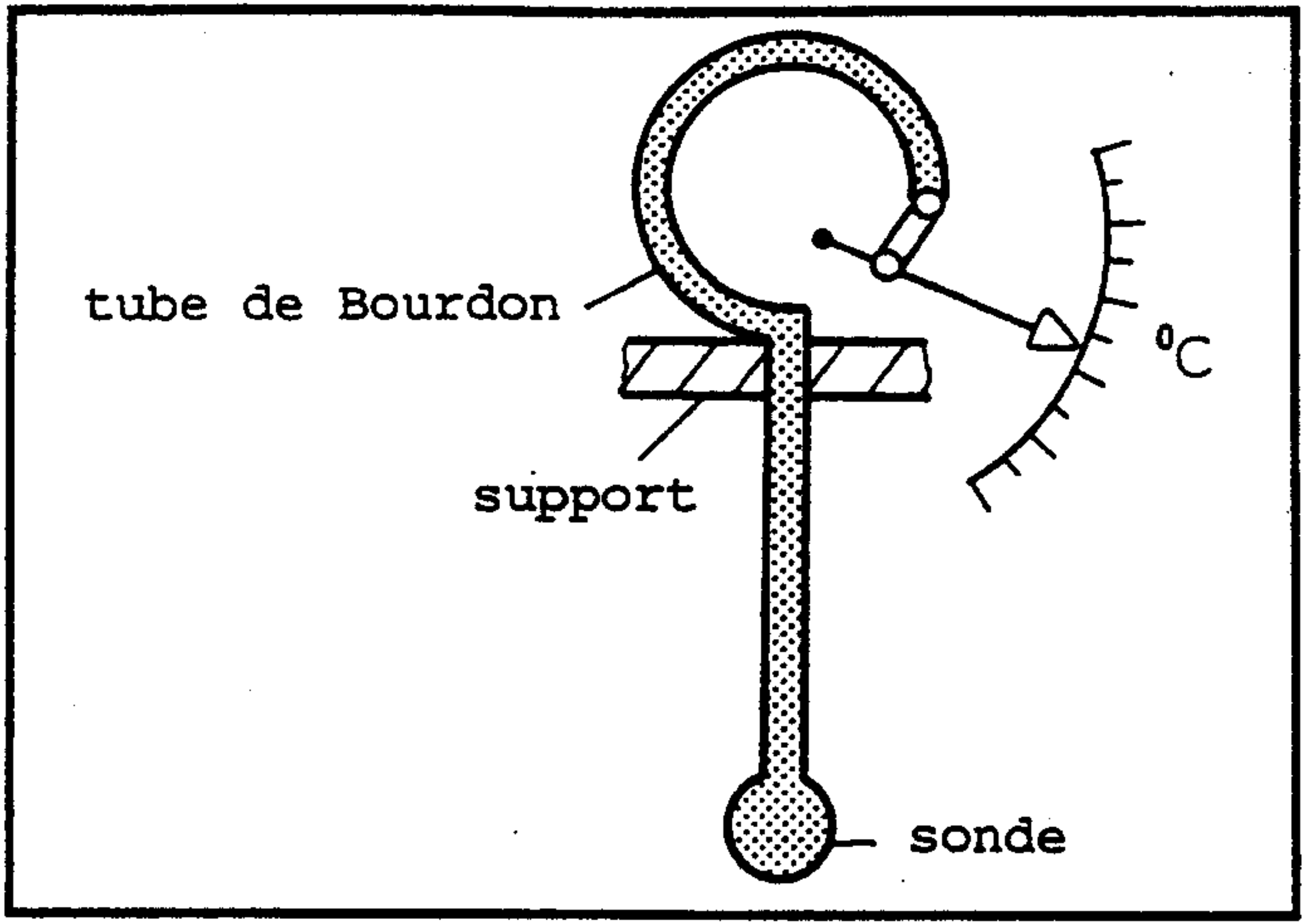


Fig. 10.5b: *Thermometer with metallic support [Spinnler, 1982, p. 18.3]*

Thermal expansion thermometer:

Calibration of liquid/glass thermometer

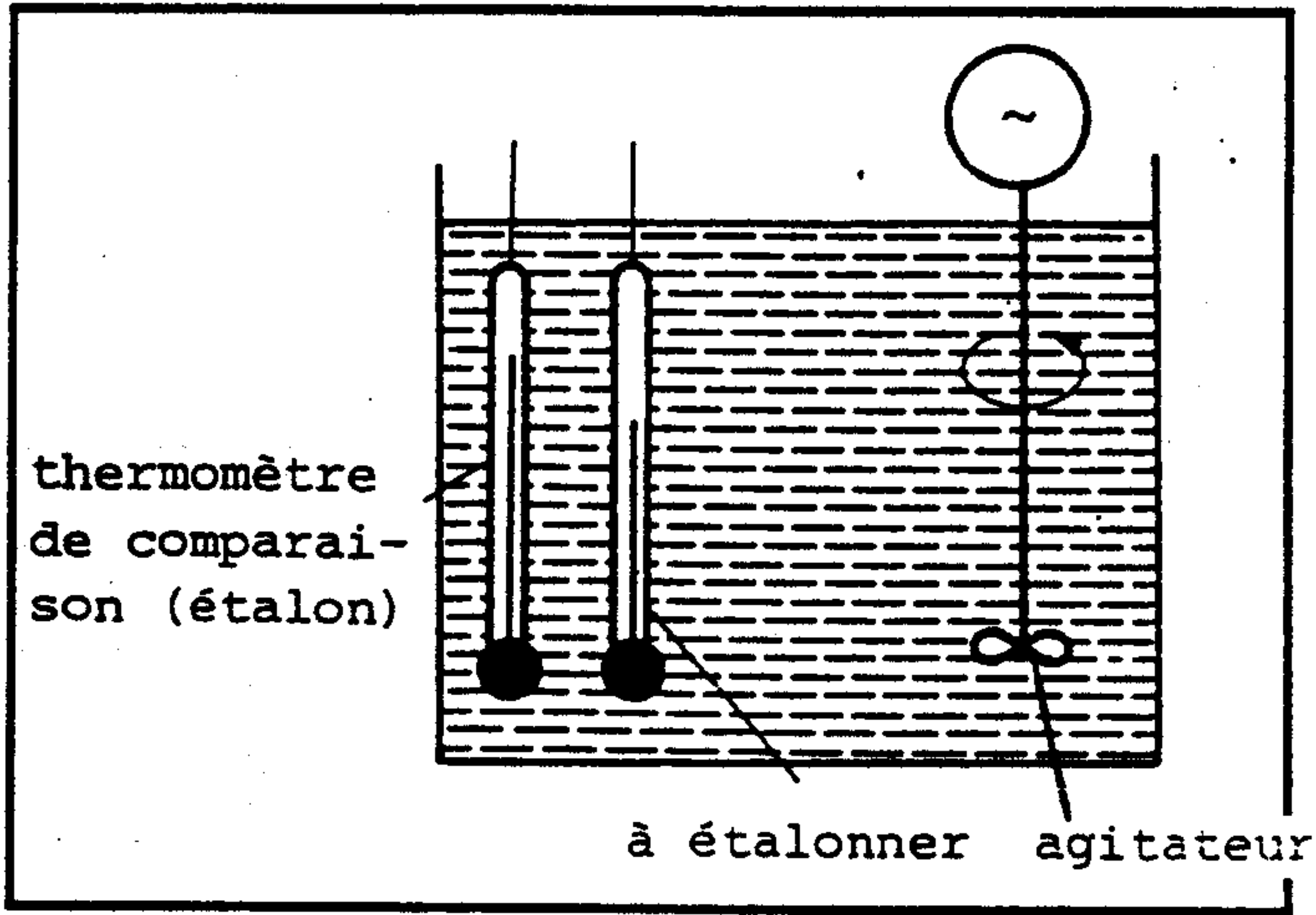


Fig. 10.6: Schematic view of a calibration bath [Spinnler, 1982, p. 18.3]

Thermal expansion thermometer:

Thorpe's correlation: $T_{true} = T_{indicated} + C_{correction}$

where $C_{correction} = k \cdot N \cdot (T_{indicated} - T_{mean,\ stem})$

Mercury

$k = 1/6250\ (°C)^{-1}$

Alcohol, toluene, pentane

$k = 1/962\ (°C)^{-1}$

Alernatively:
Calibrate at conditions similar to the actual test.

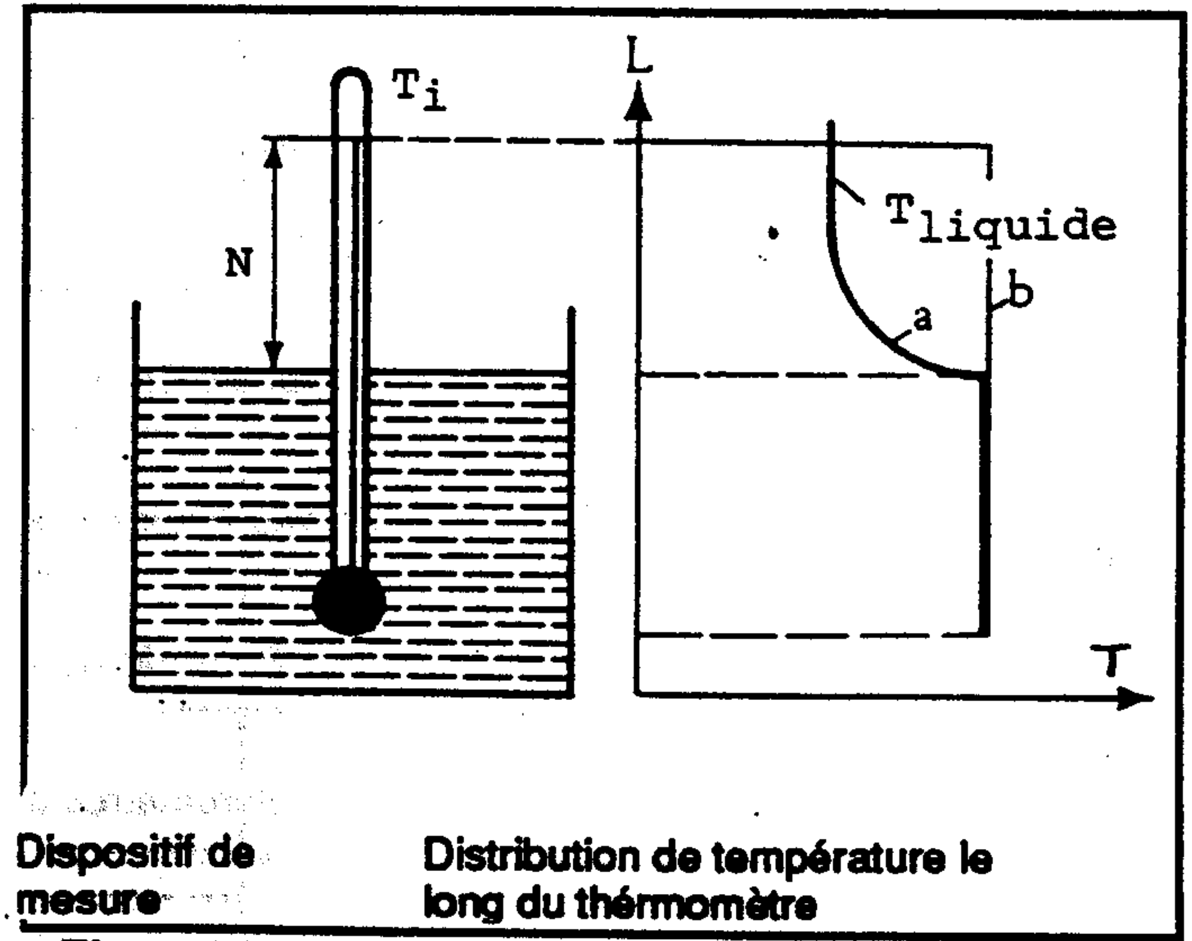


Fig. 10.7: Thorpe correlation [Spinnler, 1982, p. 18.4]

Principle:

The resistance of a metal wire depends on temperature. Usually, a Platinum wire with such length/diameter that the resistance is 100 Ohms at 0°C (Pt100). This type of sensor can be used from -200°C to +850°C.

Advantages:

- High accuracy
- Good stability in time (limited aging)
- Almost linear change of resistance with temperature

Drawbacks:

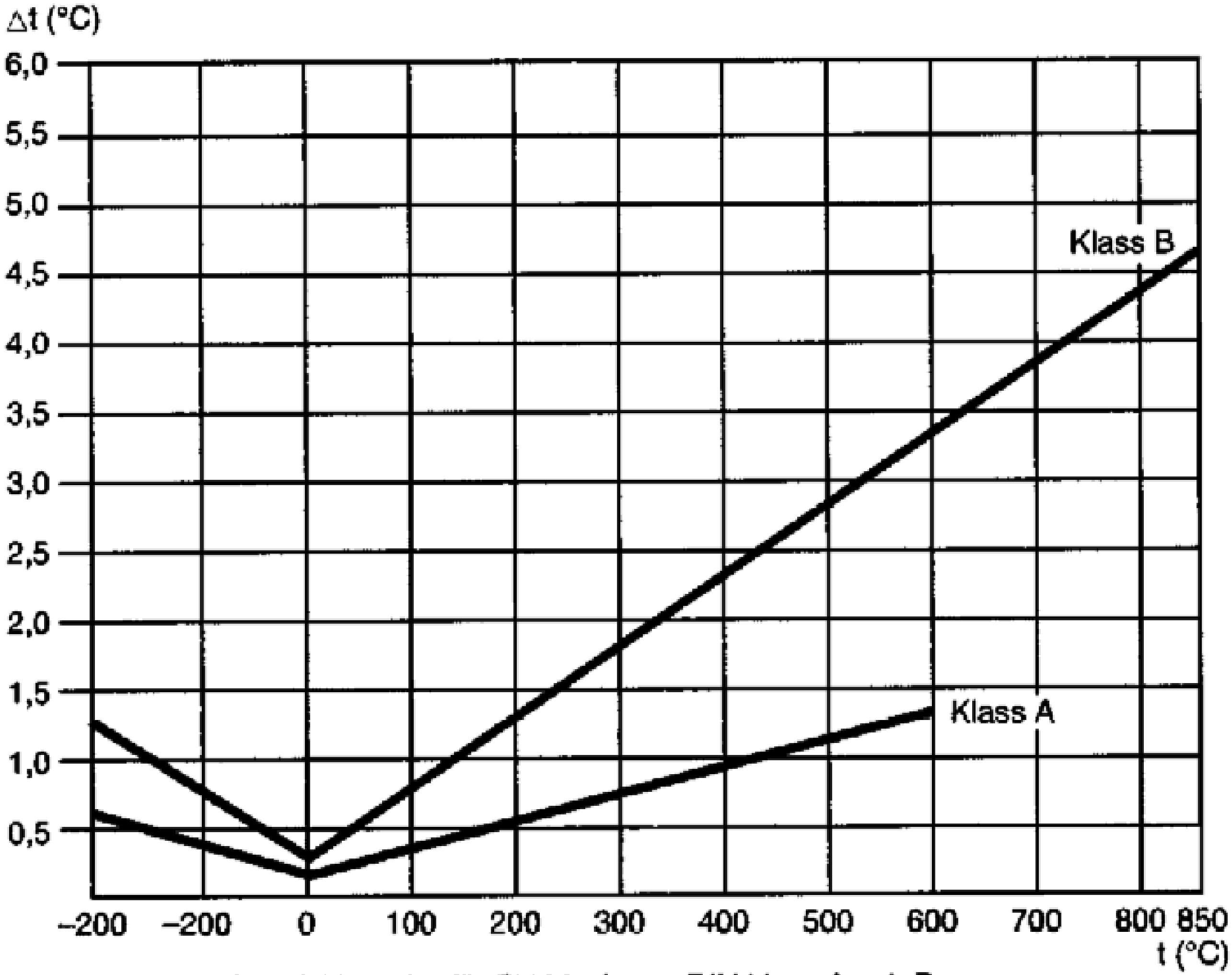
- Small change of the resistance with temperature (small signal)
- Usually large mass

Accuracy of Pt100 according to DIN norm.

Class A:
ΔT=±[0.15+0.002·|T|]°C

Class B:
ΔT=±[0.3+0.005·|T|]°C

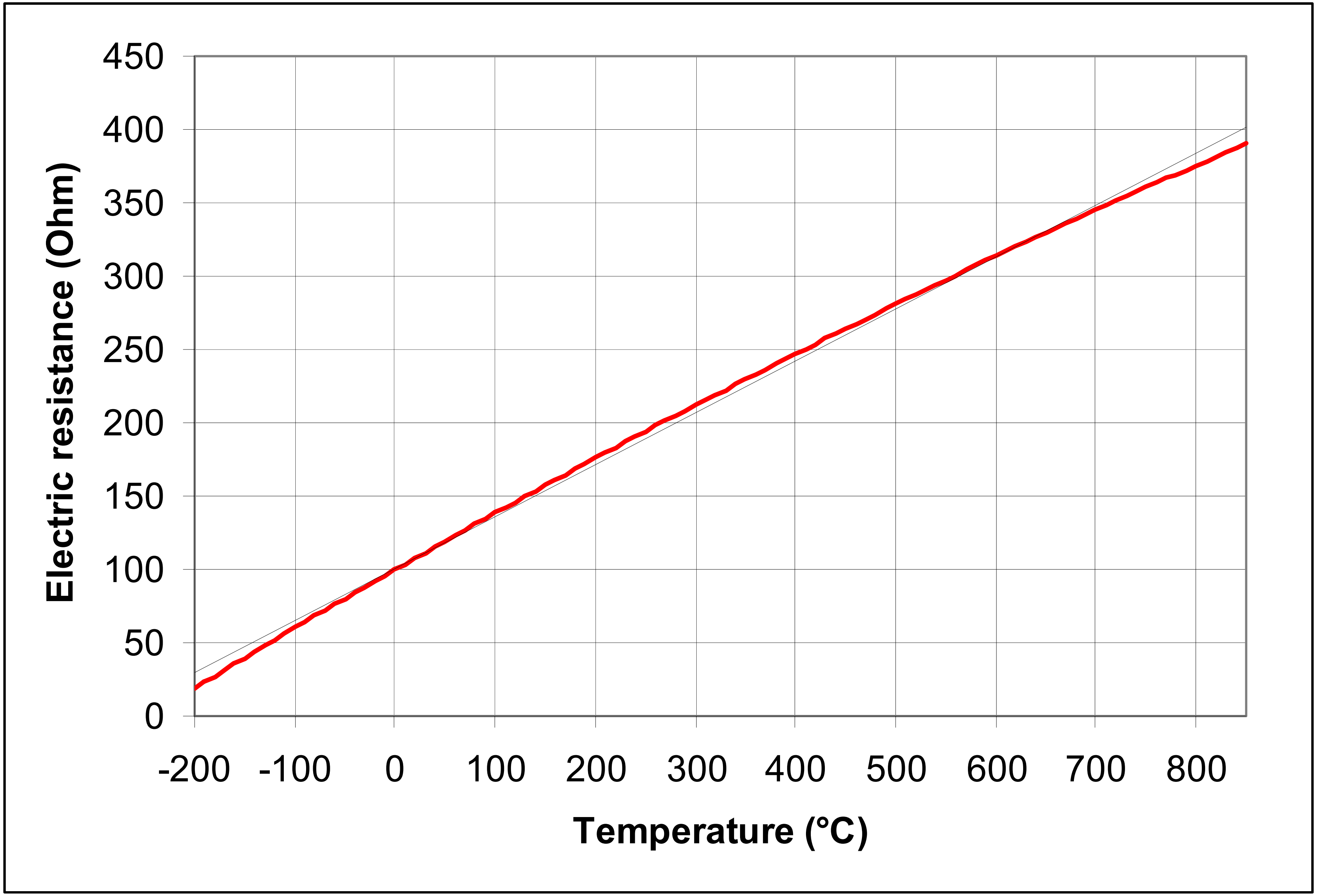
Higher accuracy also available.



Δt= Givarens tillåtna fel i grader för Pt100-givare, DIN klass A och B.

Onoggrannhet hos Pt100-givare.

Resistance of Pt100 almost linear with temperature



Resistance thermometer, cont.

Relation between resistance and temperature of Pt-100

för $-100°C < t < 0°C$:

$$R_t = R_0\,(1 + At + Bt^2 + C(\,t - 100)\,t^3)$$

för $0°C < t < 850°C$:

$$R_t = R_0\,(1 + At + Bt^2\,)$$

där

R_t är resistansen vid temperaturen t

R_0 är resistansen vid 100°C

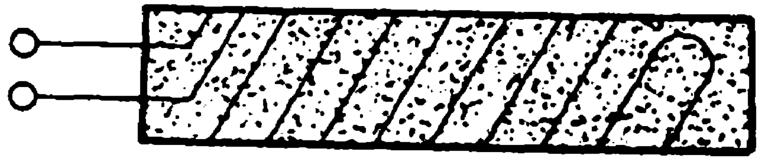
$A = 3{,}90802 \times 10^{-3}\,/\,°C$

$B = -5{,}802 \times 10^{-7}\,/\,°C^2$

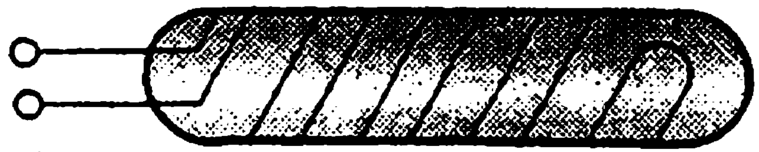
$C = -4{,}27350 \times 10^{-12}\,/\,°C^4$

Resistance thermometer, cont.

To achieve a high accuracy the platinum wire must not be locked in a certain position. This increases the risk of damage. Precision thermometers of this type are <u>extremely</u> chock sensitive.



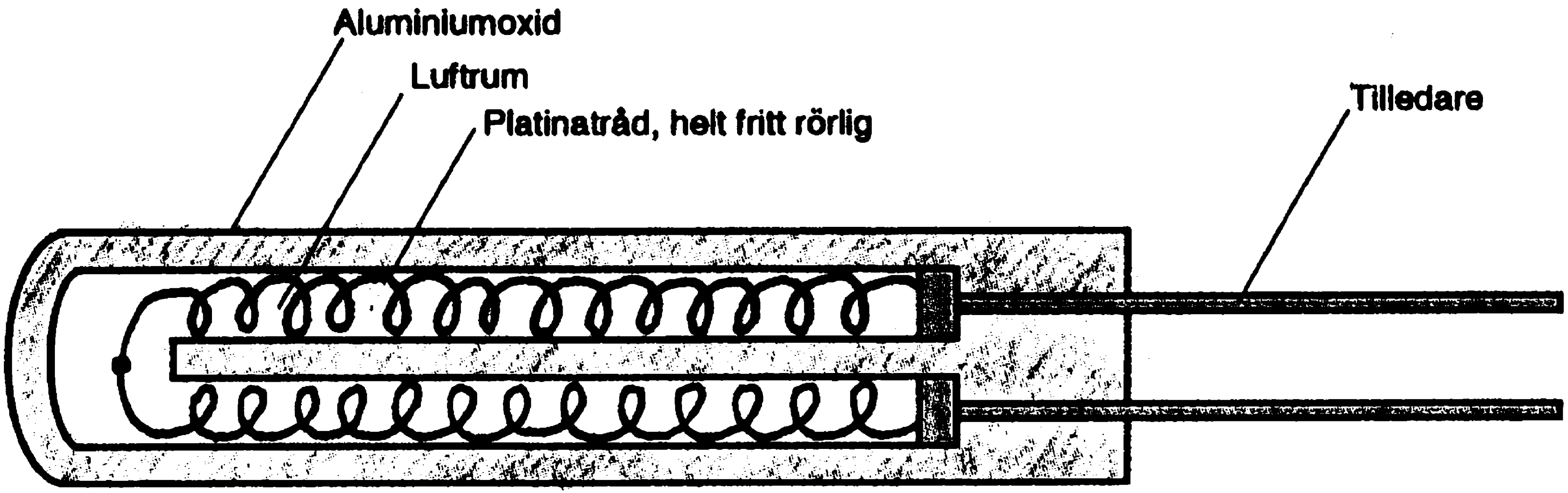
a: Flat aluminium support to measure the temperature of the surface on which the wire is glued



b: Cylindrical element. The wire surrounds a material such as glass (up to 500°C), ceramic (up to 800°C) and aluminium (up to 1100°C)

Fig. 10.10: Resistance wire rolled onto an isolating support [Spinnler, 1982, p. 18.7]

Resistance thermometer, cont.



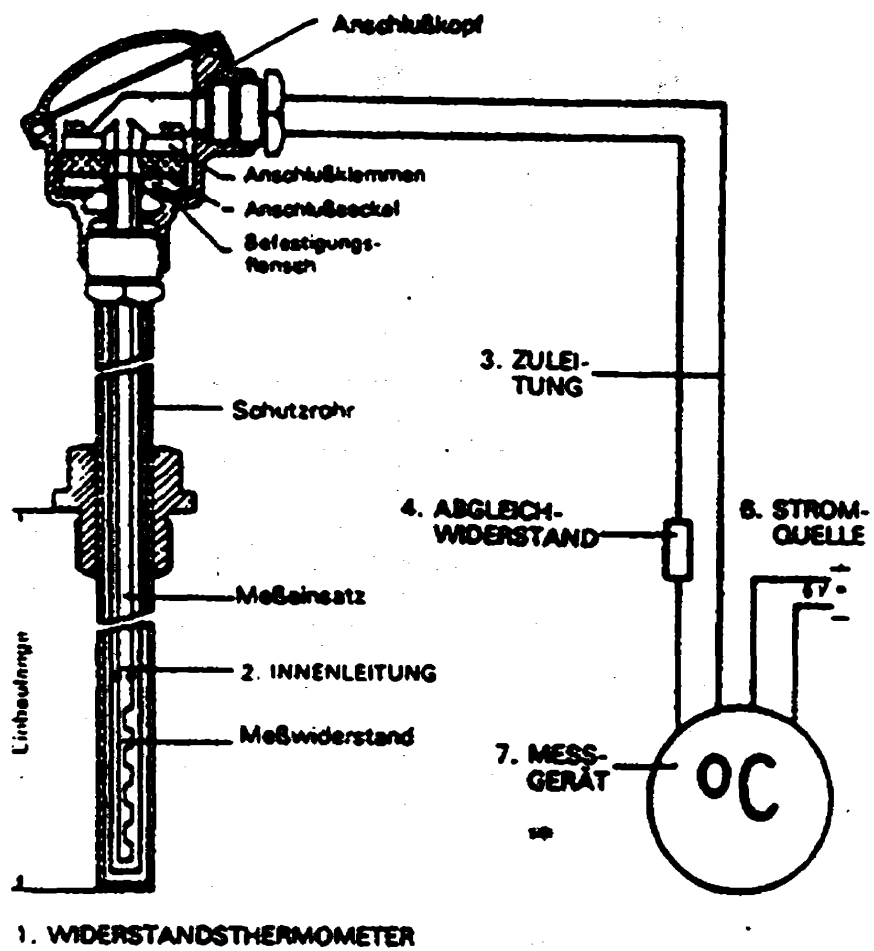
Referensgivaren för kalibrering heter SPRT, en extremt nog-grann och ömtålig platinaresistanstermometer. Den fritt upp-hängda tråden ger minimal hysteres.

Reference sensor for calibration. Extremely accurate and extremely fragile. The loosely hanging spiral of platinum wire gives minimum hysteresis.

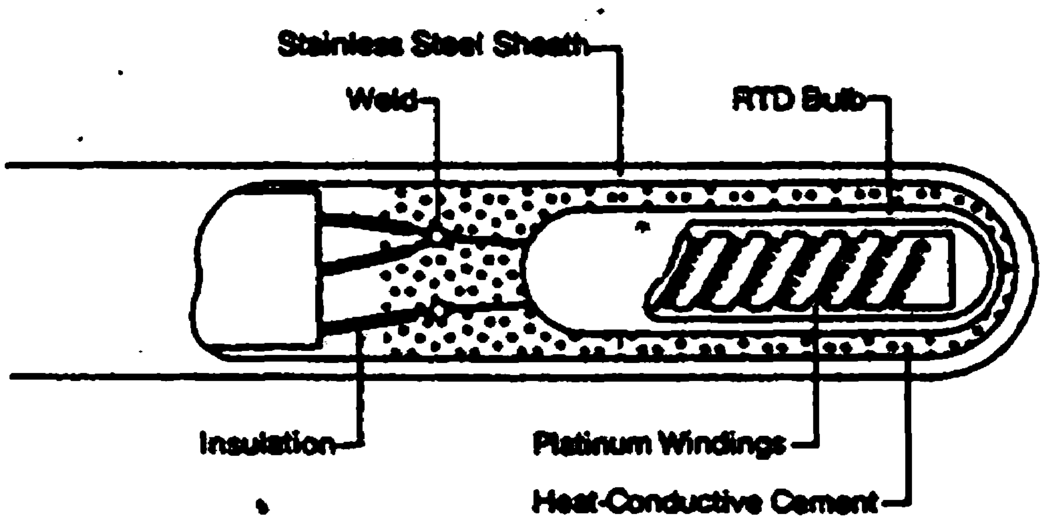
Resistance thermometer, cont.

The hysteresis of a Pt100 depend on whether the wire is fixed or not.

Expected hysteresis in % of range:
1. Wire-wound: 0.008%:
2. Bobbin: 0.08%
Film: 0.04-0.08%



a: *Global probe [Kraus and Obrowski, 1981, p. 92]*



b: Measurement of a probe head in platinum [ThermoElectric, 1989, p. K-79]

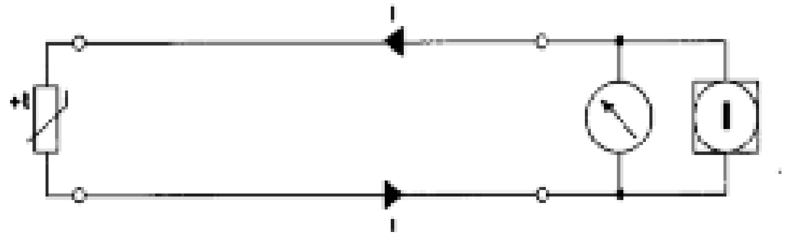
***Fig. 10.11:* Schematic system for an electric resistance thermometer of metal**

Examples of resistance thermometers (Pt100)

Resistance thermometers, cont.

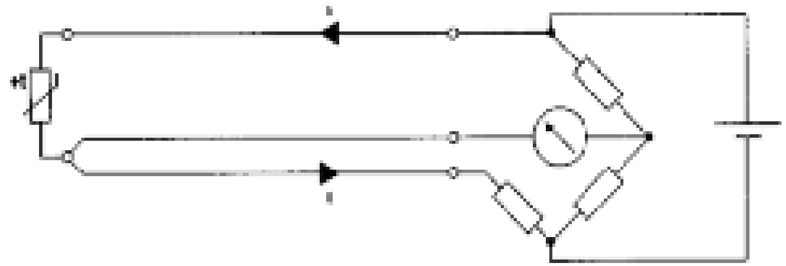
The resistance thermometer is connected in either of three ways:

Two-wire connection:



2-ledarkoppling
Mätströmmen leds i samma ledare som spänningen över motståndet mäts med. Spänningsfall i ledarna orsakar felvisning om ledarna är för långa.

Three-wire connection:



3-ledarkoppling
En Wheatstone-brygga kan på detta sätt kompensera för ledningsresistansen. Spänningen mäts högimpedivt.

Four-wire connection:

4-ledarkoppling
Mätströmmen leds i två ledare och spänningen mäts högimpedivt med de två andra ledarna. Hög mätnoggrannhet kan uppnås.

Error sources and typical error intervals according to Pentronics Temperature handbook 1.

Error source		Error
General design or installation		0.1 – 3°C
Pt100 sensor		0.03 – 0.3°C at 0°C
Cables	2-wire	0.1 – 5°C
	3-wire	0.01 – 0.5°C
	4-wire	≈0.000°C
Instrument		0.03 – 0.3°C

Thermistors:

Principle:

Ceramic semiconductors for which the resistance change with temperature. (Usually decreasing with increasing temperature).

Advantages:

- The resistance is strongly related to temperature.
- Several different types etc.
- May be very accurate.

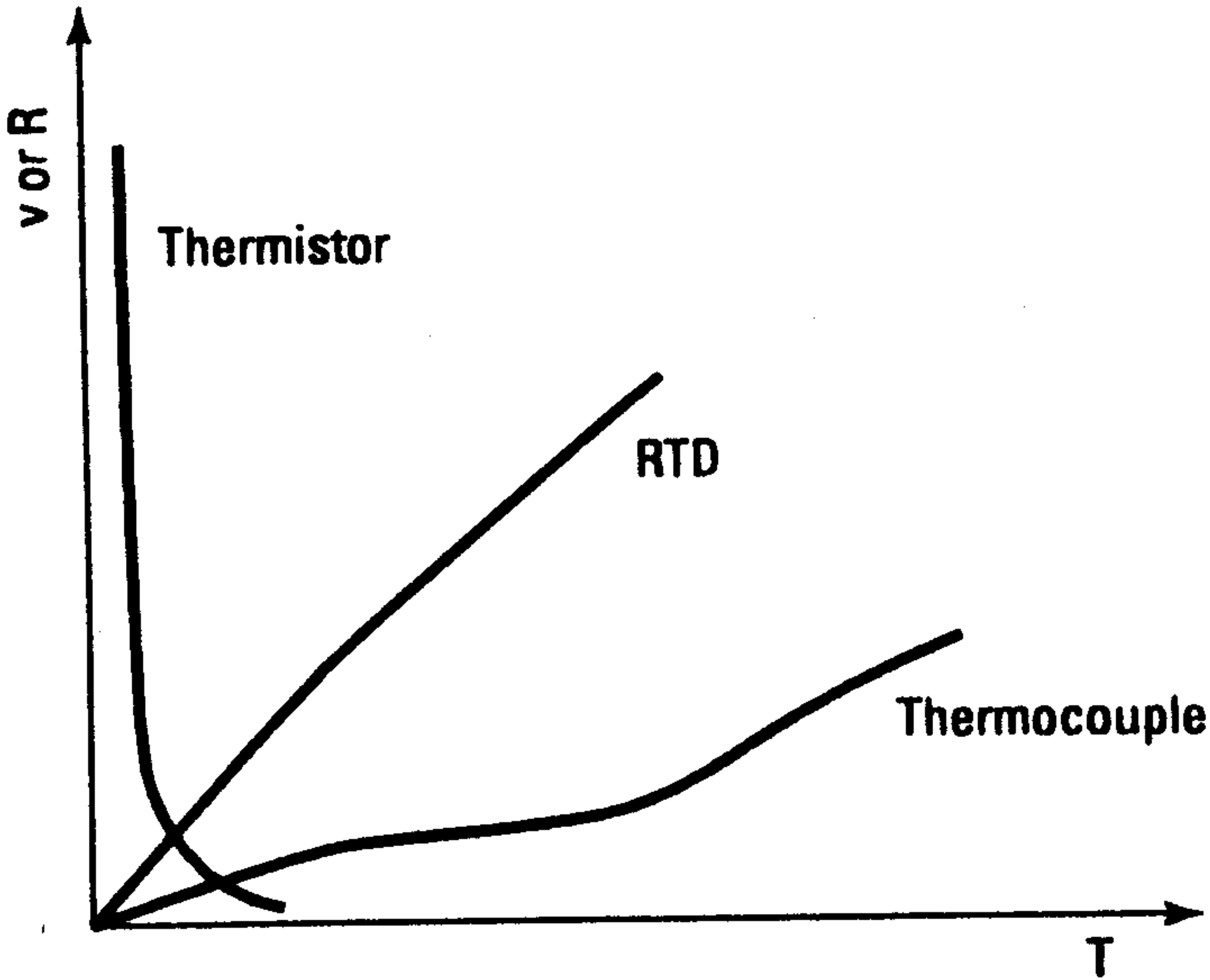
Drawbacks:

- Often extremely nonlinear.
- Individual calibration often necessary

Temperature range: -50 - 300°C

Thermistors:

Thermistors give high signal, but highly unlinear.



Thermistors:

Relation between temperature and resistance for thermistors:

$$\frac{1}{T} = A + B \cdot (\ln R) + C \cdot (\ln R)^3$$

Where A, B and C are curve fitting constants

Principle:
The Seebeck effect: If a circuit consists of two dissimilar metals and the connecting junctions are at different temperatures, a current is induced in the circuit (thermo-EMF). With a volt-meter in the circuit, an electric potential, proportional to the temperature difference, can be detected.

Actually, the thermo-EMF is generated not at the junctions but at the *temperature gradients* along the wires.

Therefore the purity of the metal (or composition of the alloy) must be the *same along the whole wire.*

The Seebeck Effect

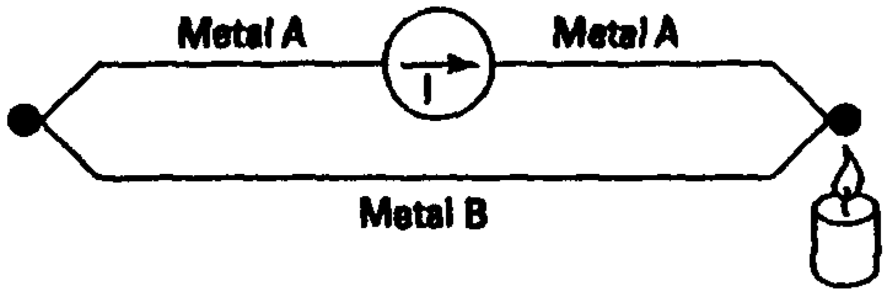
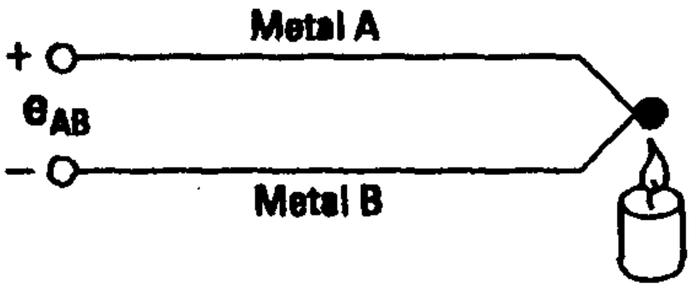
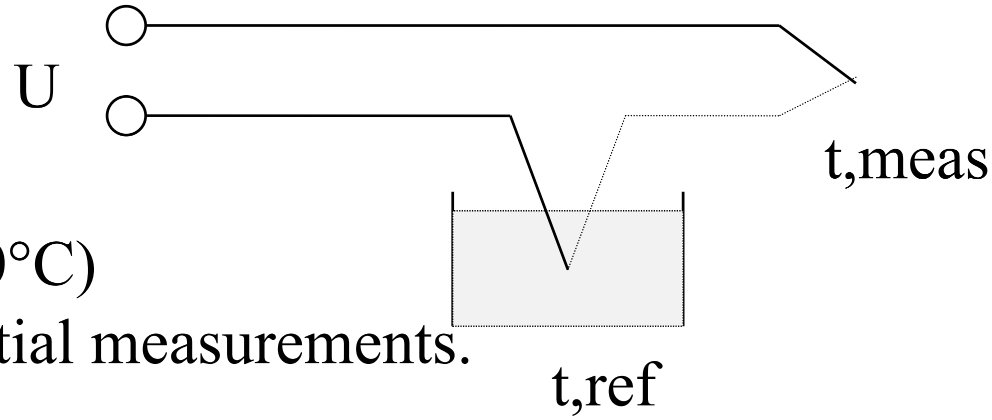


Figure 3



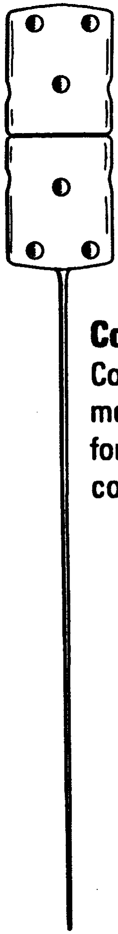
e_{AB} = Seebeck Voltage

Thermocouples

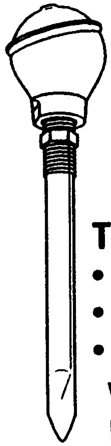


Advantages:
- May be very small
- Low cost per sensor
- Large temperature span (-200 - 1700°C)
- May give high accuracy for differential measurements.

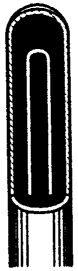
Drawbacks:
- Small signal (<0.05mV/°C). Risk of electric disturbances.
- Nonlinear signal
- Known reference temperature required.



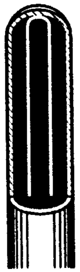
Connector
Composed of same metals as thermocouple, for minimum connection error.



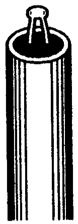
Thermocouple Well
- lower gradient
- protects wire
- change thermocouple without interrupting process



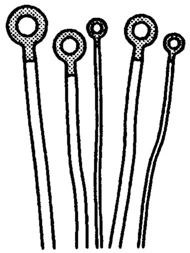
Undergrounded Junction
- best protection
- electrically isolated



Grounded Junction
- wires protected
- faster response



Exposed Junction
- wires unprotected
- fastest response



Thermocouple Washers
- couple built into washer
- convenient mounting

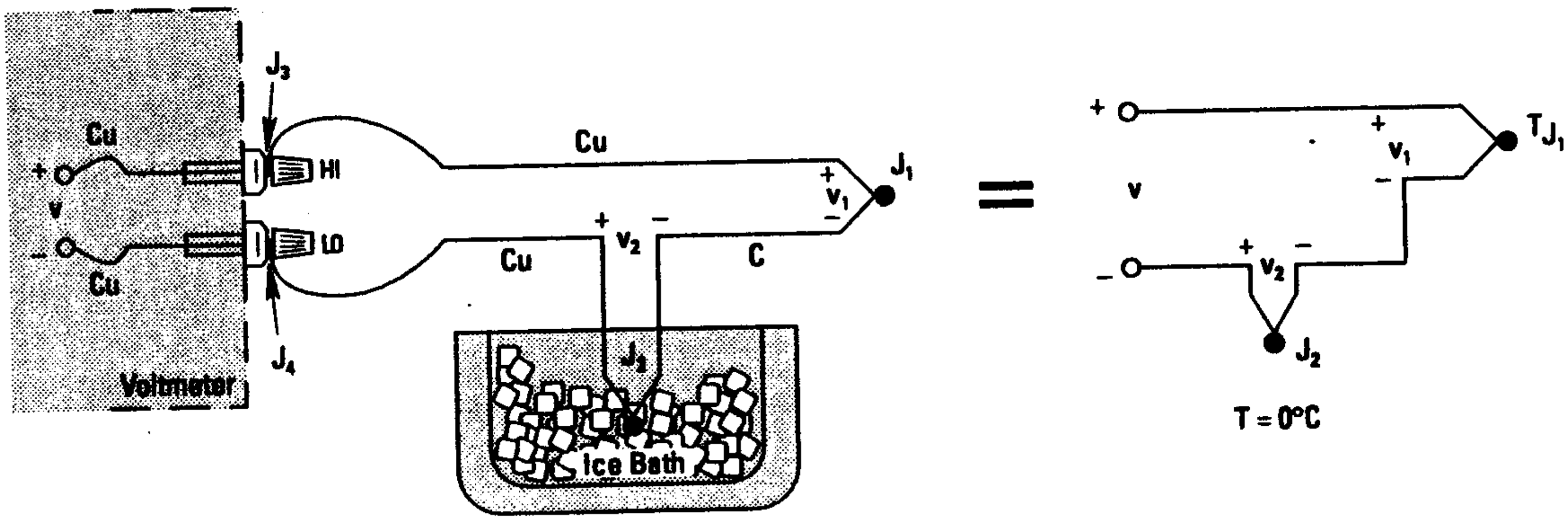
Several different combinations of metals/alloys are used as thermocouples. Most common are types J, K, T and, for high temperatures, S.

Type	Metal/alloy	Temperature range	EMF (mV) at 100°C/0°C
J	Iron/Konstantan	0-760°C	5.268
K	Chromel/Alumel	-200 - 1260°C	4.095
T	Copper/Konstantan	-200 - 370°C	4.277
S	Platinum/Rhodium-Platinum	0-1480°C	0.645

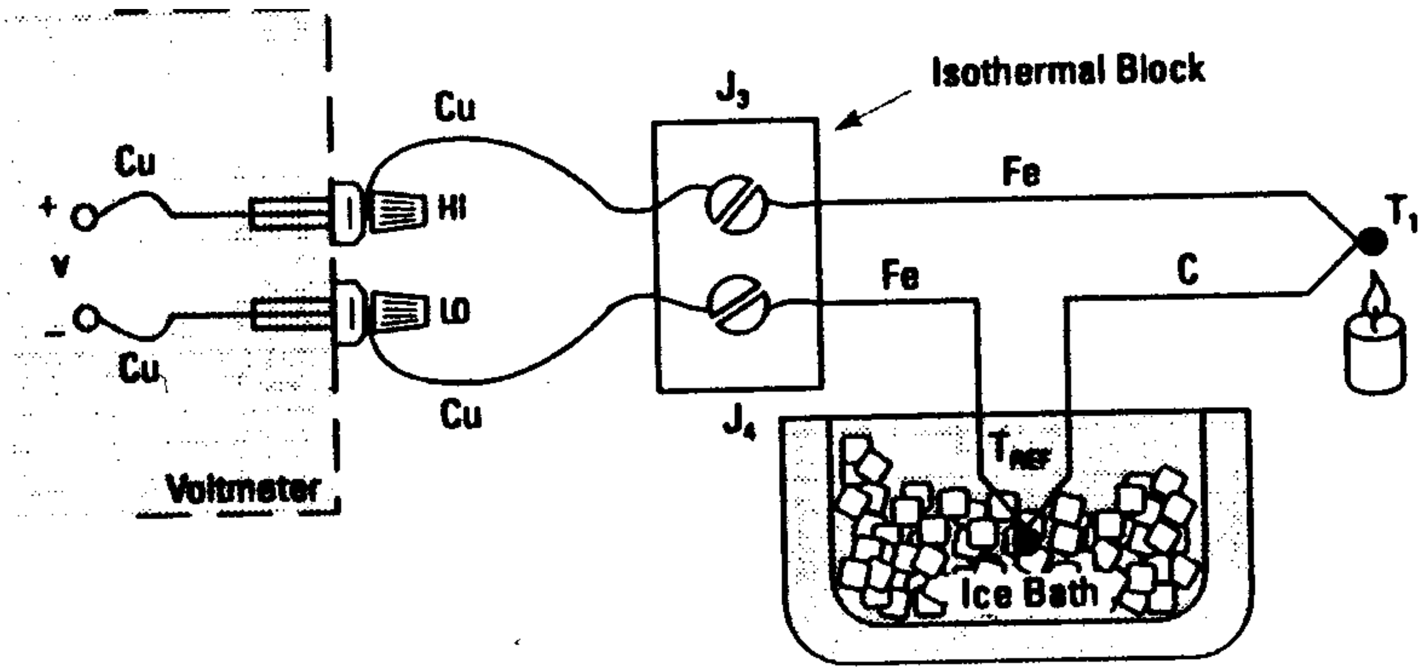
(Konstantan=copper-nickel alloy
Chromel=nickel-chromium alloy
Alumel=nickel-aluminum alloy)

Thermocouples:

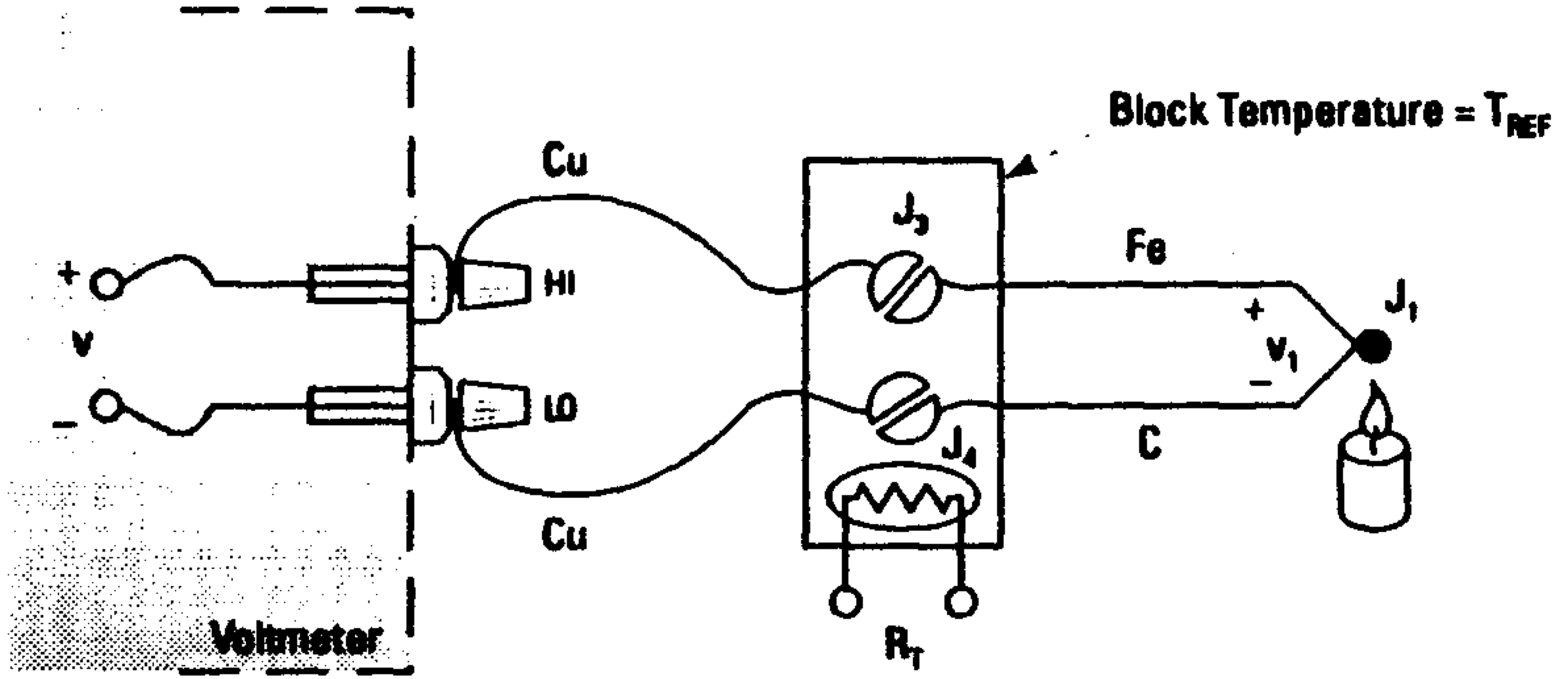
External Reference Junction



Thermocouples:



External Reference Junction - No Ice Bath



Signals from thermocouples:

The voltage from a thermo*couple* depends on the temperature *difference* between the two junctions and on the temperature of the reference junction.
The voltage is transferred to temperature by aid of tables or polynomials based on the assumption that the reference junction is at t=0°C.

Type E Thermocouple

mV	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.10	mV
	Temperatures in Degrees C (ITS-90)											
0.00	0.00	0.17	0.34	0.51	0.68	0.85	1.02	1.19	1.36	1.53	1.70	0.00
0.10	1.70	1.87	2.04	2.21	2.38	2.55	2.72	2.89	3.06	3.23	3.40	0.10
0.20	3.40	3.57	3.74	3.91	4.08	4.25	4.42	4.59	4.76	4.92	5.09	0.20
0.30	5.09	5.26	5.43	5.60	5.77	5.94	6.11	6.28	6.45	6.61	6.78	0.30
0.40	6.78	6.95	7.12	7.29	7.46	7.63	7.79	7.96	8.13	8.30	8.47	0.40
0.50	8.47	8.64	8.80	8.97	9.14	9.31	9.48	9.64	9.81	9.98	10.15	0.50
0.60	10.15	10.32	10.48	10.65	10.82	10.99	11.15	11.32	11.49	11.66	11.82	0.60
0.70	11.82	11.99	12.16	12.33	12.49	12.66	12.83	12.99	13.16	13.33	13.50	0.70
0.80	13.50	13.66	13.83	14.00	14.16	14.33	14.50	14.66	14.83	15.00	15.16	0.80
0.90	15.16	15.33	15.50	15.66	15.83	16.00	16.16	16.33	16.49	16.66	16.83	0.90
1.00	16.83	16.99	17.16	17.32	17.49	17.66	17.82	17.99	18.15	18.32	18.49	1.00
1.10	18.49	18.65	18.82	18.98	19.15	19.31	19.48	19.64	19.81	19.98	20.14	1.10
1.20	20.14	20.31	20.47	20.64	20.80	20.97	21.13	21.30	21.46	21.63	21.79	1.20
1.30	21.79	21.96	22.12	22.29	22.45	22.61	22.78	22.94	23.11	23.27	23.44	1.30
1.40	23.44	23.60	23.77	23.93	24.10	24.26	24.42	24.59	24.75	24.92	25.08	1.40

Thermocouples:

NIST ITS-90 Polynomial Coefficients

Thermocouple Type	Type J		Type K	
Temperature Range Error Range Polynomial Order	-210°C to 0°C ±0.05°C 8th order	0°C to 760°C ±0.04°C 7th order	-200°C to 0°C ±0.04°C 8th order	0°C to 500°C ±0.05°C 9th order
c_0	0	0	0	0
c_2	1.9528268×10^{-2}	1.978425×10^{-2}	2.5173462×10^{-2}	2.508355×10^{-2}
c_1	$-1.2286185 \times 10^{-6}$	-2.001204×10^{-7}	$-1.1662878 \times 10^{-6}$	7.860106×10^{-8}
c_3	$-1.0752178 \times 10^{-9}$	1.036969×10^{-11}	$-1.0833638 \times 10^{-9}$	$-2.503131 \times 10^{-10}$
c_4	$-5.9086933 \times 10^{-13}$	$-2.549687 \times 10^{-16}$	$-8.9773540 \text{ v } 10^{-13}$	8.315270×10^{-14}
c_5	$-1.7256713 \times 10^{-16}$	3.585153×10^{-21}	$-3.7342377 \times 10^{-16}$	$-1.228034 \times 10^{-17}$
c_6	$-2.8131513 \times 10^{-20}$	$-5.344285 \times 10^{-26}$	$-8.6632643 \times 10^{-20}$	9.804036×10^{-22}
c_7	$-2.3963370 \times 10^{-24}$	5.099890×10^{-31}	$-1.0450598 \times 10^{-23}$	$-4.413030 \times 10^{-26}$
c_8	$-8.3823321 \times 10^{-29}$		$-5.1920577 \times 10^{-28}$	1.057734×10^{-30}
c_9				$-1.052755 \times 10^{-35}$

Temperature Conversion Equation: $t_{90} = c_0 + c_1 x + c_2 x^2 + \ldots + c_9 x^9$

Nested Polynomial Form (4th order example): $t_{90} = c_0 + x(c_1 + x(c_2 + x(c_3 + c_4 x)))$

Compensation wire:

Certain types of TC-wires are very expensive. To reduce the cost *compensation wire* is often used. This is a less expensive wire which has the same Seebeck coefficient at temperatures around ambient.

Example: Error due to compensation wire used through the wall of a furnace. (an aged TC wire in the wall of the furnace may also give an error).

Sources of error using thermocouples:

- Reference temperature incorrect
- Mix of thermocouple types
- Compensation wire in too high temperature
- Oxidized wires
- Electric disturbances
-
- Open circuit
- Short circuit
- Wrong polarity at instrument
- Wrong polarity at connection within circuit

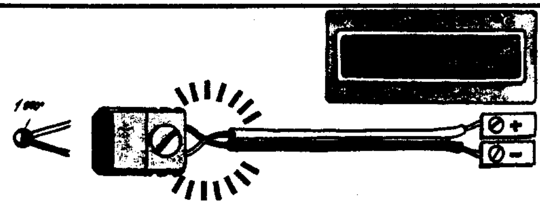
Sources of error using thermocouples:

- Open circuit
- Short circuit
- Wrong polarity at instrument
- Wrong polarity at connection within circuit
- Doubly wrong polarity

Felkopplingar

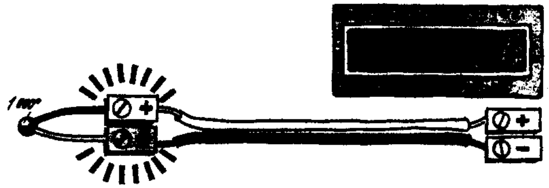
Avbrott
Givartråden har gått av, lossnat eller har dålig kontakt med instrumentet. Moderna instrument larmar t ex genom att skriva "Open" på skärmen.

Kortslutning
Om isoleringen nöts av och trådarna kortsluts, uppstår en mätpunkt på detta ställe. Instrumentet visar temperaturen i kortslutningspunkten istället för i givarspetsen.

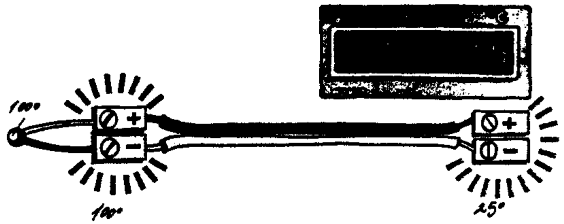


Polvändning av hela mätkretsen
Vid polvändning går instrumentet "baklänges". En temperaturökning registreras som minskad temperatur.

Polvändning inom mätkretsen
Anslutningskabeln måste ha samma polaritet som termoelementtrådarna. Om termoelementet är polvänt får man motverkande spänningar. Avläst värde blir temperaturen i kopplingshuvudet minus mätpunktens temperatur.



Dubbel polvändning
Om anslutningskabeln är polvänd i bägge ändar påverkar ändpunkternas temperatur också signalen. Avläst värde blir mätpunktens temperatur minskad med dubbla temperaturskillnaden mellan kopplingshuvud och referenspunkt. Tänk på att en inkopplad temperaturregulator med börvärdet 1000°C skulle reglera upp effekten så att ärvärdet blir ca 150°C över börvärdet. Trots detta visar indikatorn 1000°C.



Calibration at authorized laboratory:
For accurate calibration the temperature measurement equipment should be sent to an authorized laboratory. There, the calibration is usually done by *comparing* with an accurate platinum thermometer, which in turn has been calibrated against a platinum thermometer at a national center (SP in Sweden). This thermometer is calibrated against the fix points according to ITS-90.
The calibrated equipment may then be used for comparative calibrations of other sensors and instruments.
During the comparative calibration both sensors are placed in a well stirred liquid bath. It is important that both sensors are lowered far into the liquid to reduce the influence of conduction along the sensor.

Simple one-point calibration:
If other references are not available the sensor may be calibrated at 0°C against an ice bath. A well stirred ice bath with mostly crushed ice of tap water has a temperature between 0 and -0.1°C.

It is a good habit to always *measure the ice temperature together with other measurements*.

Comment to eqs 10.16 10.17 and the following text:

At adiabatic conditions, the total energy (enthalpy) in the free flow must be the same as at the wall, or there is no equilibrium. As the velocity is zero at the wall the temperature there must be higher to reach the same enthalpy level. This means that the static temperature at the wall at equilibrium (and adiabatic conditions) must equal the stagnation temperature in the free flow.

References:

- Measuring Techniques in Thermal Engineering, Chapter 10, Torsten H. Fransson, 1999
- Practical Temperature Measurerments, Hewlet Packard (http://www.tmo.hp.com/tmo/Notes/English/Data_acq_AN290_pract_meas.html)
- Pentronics Temperaturhandbok1, 1997
- The International Temperature scale (http://www.electro-optical.com/unitconv/tempref/its90.html)
- About Temperature (http://www.unidata.ucar.edu/staff/blynds/tmp.html#tmp)