

# C7. Temperature measurement

## I. OBJECTIVE OF THE EXPERIMENT

We would like to study different physical systems capable of measuring temperature in a large range: platinum probe, thermocouple, gas thermometer and pyrometer

We will learn how to connect a Pt100 probe electrically and calibrate it, how to calibrate a thermocouple, how to operate a gas thermometer, and calibrate a pyrometer using a thermocouple.

## II. TEMPERATURE MEASUREMENT

Temperature is a sensorial notion, that has to do with a hot or cold feeling after a thermal contact. The idea of a *thermal contact* strikes us as important. By thermal contact is implied any process allowing heat to be exchanged between two systems (conduction, convection, radiation). If there is a thermal contact between two bodies, both of the temperature vary until they reach an equilibrium (supposing both systems are well isolated from external fluctuations). A *thermal equilibrium*, we can generalize by expressing a principle:

Two bodies in thermal contact have the same temperature.

and

If two systems A and B are in thermal equilibrium with a system C, then they are in thermal equilibrium with one another

This is the **zeroth principle of thermodynamics**

The use of thermometers is entirely based on this principle, since a thermometer can only ever indicate its own temperature.

Therefore, in order to measure a temperature, one must:

a) Choose a *system* (thermometer) that has a value that evolves with temperature. This is called the thermometric value

Examples: the volume of a liquid (alcohol thermometer), the resistance of a wire (resistance thermometer), the pressure of a gas at constant volume (gas thermometer).

b) Choose *fixed arbitrary points* (triple point of water, boiling temperature of water at atmospheric pressure, etc...) and give those points an arbitrary value (Triple point of water: 273.16 K).

c) In order to describe the temperature in between, choose an arbitrary *conversion law* linking the thermometric value to the temperature.

Fixed point allowing the calibration of thermometers

<b>Substance</b>	<b><math>T</math> [°C]</b>
* Boiling Nitrogen	-195,8
* Acetone + solid CO <sub>2</sub>	- 86
* Melting Ice	- 0,01
* Boiling water at 720 torr	98,5
* Melting point of tin	213,9
* Melting point of lead	327,5
* Melting point of zinc	419,6
* Melting point of sulfur	444,7
* Melting point of aluminum	660,4
* Melting point of silver	961,9
* Melting point of gold	1064,4
* Melting point of copper	1084,5
* Melting point of platinum	1772

**III. EXEMPLES DE THERMOMETRES:****III.1. Mercury thermometer**

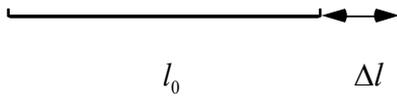
Supposing that the volume of mercury varies linearly with the temperature  $T$  :

$$T = \frac{V - V_0}{V_{100} - V_0} \cdot 100 \quad (T \text{ en } [^{\circ}\text{C}])$$

where  $V_{100}$  = volume of mercury at boiling point of water

and  $V_0$  = volume of mercury in melting ice

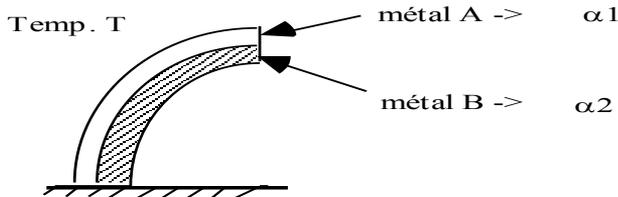
**III.2. Expansion of a metal.**



$$\frac{\Delta l}{l} = \alpha(T - T_0)$$

$\alpha$  determined through calibration

Bimetal:



Since  $\alpha_1$  is different from  $\alpha_2$  (here  $\alpha_1 > \alpha_2$ ), we notice a curvature proportional to  $T$ .

**III.3. Thermosensor of resistance thermometer**

The electrical resistance of a body generally varies with temperature. For example, the resistance of a tungsten filament is 12 times higher at its working temperature (2000 °C) compared to room temperature, conversely, the resistance of a coal filament becomes 9 smaller when heated up to 1800 °C constantan (Ni – Cu alloy) has a resistance practically independent of temperature (thus the name).

The measure of resistance can be done with great precision and variations of the order of a hundredth of a degree are detectable. The most widespread resistance thermometers are those with a *pure platinum wire*. The resistance is measured using a Wheatstone bridge

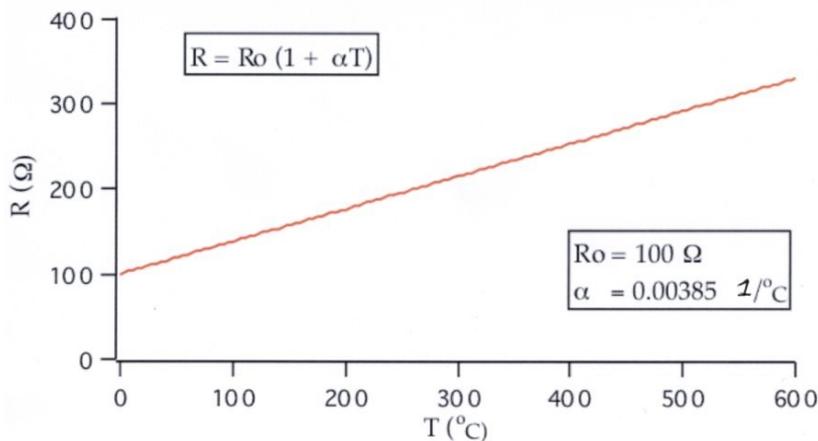


Fig. 1: Electrical resistance  $R$  of a  $100 \Omega$  platinum probe (Pt<sub>100</sub>)

**Pros:**

- stable
- precise
- linear

**Cons :**

- bulky
- current source required
- self-heating mechanism

**III.4. Thermocouple (or thermoelectric couple)**

**Principle:** A temperature difference  $\Delta T$  between the extremities of a conductor (Fig. 2) leads to a difference of electric potential  $\Delta V$  :

$$\Delta V = S \cdot \Delta T$$

where  $S$  is the Seebeck coefficient, specific for each conductor.

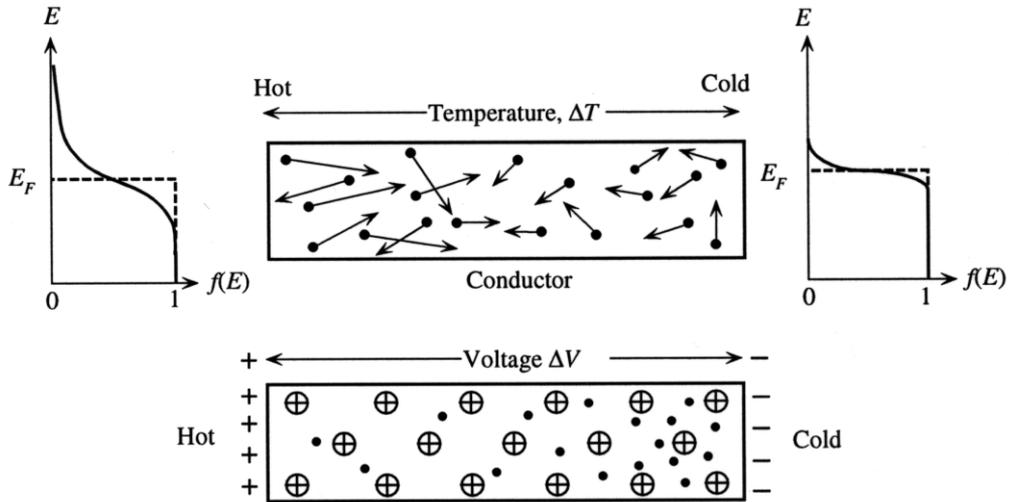


Fig. 2: The Seebeck effect. A temperature gradient  $\Delta T$  along a conductor gives rise to a potential difference  $\Delta V$ .

Therefore, if we make a circuit out of two metals A and B (Fig. 3), one end of which is placed at a fixed temperature  $T_0$  and the other end a temperature  $T$ , we notice a thermoelectric voltage  $\mathcal{E} = f(T - T_0)$ , measurable with a precision microvoltmeter, that can sometimes reach 50 mV/K. This phenomenon, noticed for the first time by Seebeck in 1821, is called Seebeck effect.  $\mathcal{E}$  is called the Seebeck voltage.

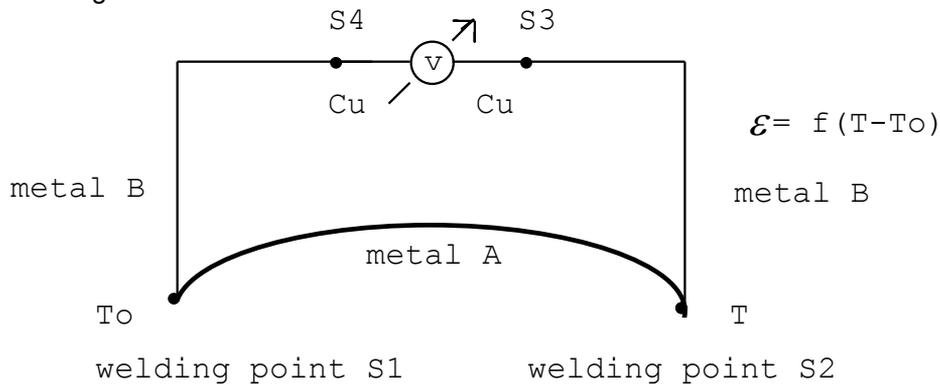


Figure 3: Measurement of Seebeck voltage

Range of measurable temperatures: This range is limited at low temperature by the low detectability of the thermoelectric fluctuations and at high temperature by the melting points of the different metals.

*Choosing metals:* the choice of metals is influenced by the following considerations:

- The weld must resist to the thermal fluctuations in the using range, and conserve all of its properties after an extended period of use.
- The thermoelectric tension must be as high as possible, and vary continuously with the temperature
- If possible, we choose inexpensive materials

Possible combinations : Here are the most widespread

Metals	Range of temperatures in [°C]
"copper <-> constantan (60 % Cu + 40 % Ni)"	- 200 à 600
"copper <-> iron"	- 200 à 700
"nickel-chrome (90 % Ni + 10 % Cr) <-> constantan"	- 200 à 700
"nickel-chrome <-> nickel"	- 200 à 1100
"chromel (89 % Ni + 10 % Cr + 1 % Fe) <-> alumel (94 % Ni + 2 % Al + 1 % Si + 2,5 % Mn + 0,5 % not indicated)" (Hoskins couple)	- 200 à 1200
"rhodium platinum(90 % Pt + 10 % Rh) <-> platinum"	+ 200 à 1600

**Sources of errors:** There are diverse sources for the errors

Here are the main ones:

- We need to make sure the reference temperature remains constant  $T_0$  (ice water is a good reference point).
- some gases can interact with one or both of the metals, and vary its properties; this is why the cables are always sheathed (e.g. quartz, etc.).
- The connections  $S_1$  and  $S_2$  with the microvoltmeter B (see fig. 3) can provoke parasitic thermoelectric voltages, that are luckily negligible at room temperature. There exist several ways to get rid of these voltages (see Fig. 5).
- The resistance of the microvoltmeter isn't infinite in comparison to that of the thermocouple. For more precise results, use a compensation potentiometer, that counteracts the voltage of the thermocouple

The response of a thermocouple is generally non-linear and depends on the selected couple.

**In short:**

Thermocouples present the following characteristics:

**Pros**

- self supplied power
- simple
- robust
- cheap
- large variety of different thermocouples
- large range of temperatures

**Cons**

- non-linear response
- low thermoelectric tension
- unstable
- low sensibility

**Improving the thermocouple**

Empirical law on intermediary metals: This law states that a third metal Z, placed between two different metals X and Y of a thermocouple, doesn't modify the measured thermoelectric voltage, as long as the two new solders  $S_I$  and  $S_{II}$  are at the same temperature. Consequently, the circuit shown in fig. 4a is equivalent to that in fig. 4b.

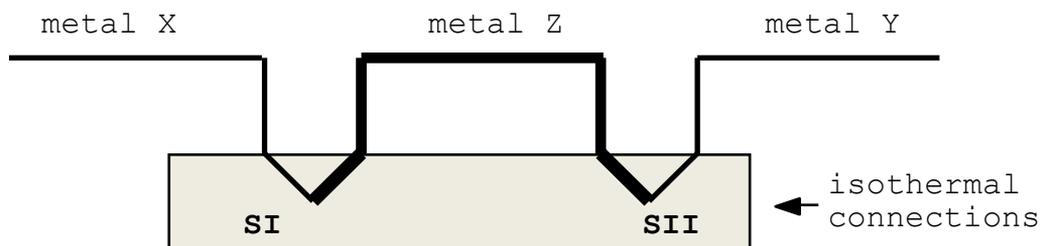


Fig. 4a: Insertion of intermediary metal Z

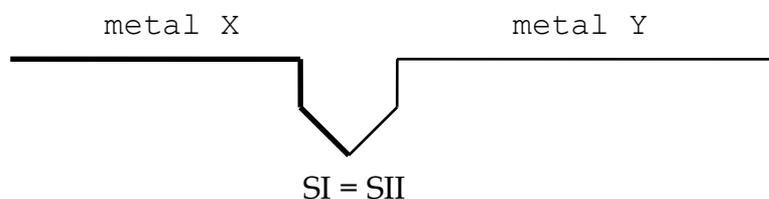


Fig. 4b: Equivalent circuit

Consequently, the circuit in fig. 3 can be replaced by that of fig. 4.

All that is left to do is extend the junctions  $S_3$  and  $S_4 = S_1$  in the ice water, or any other area of constant temperature.

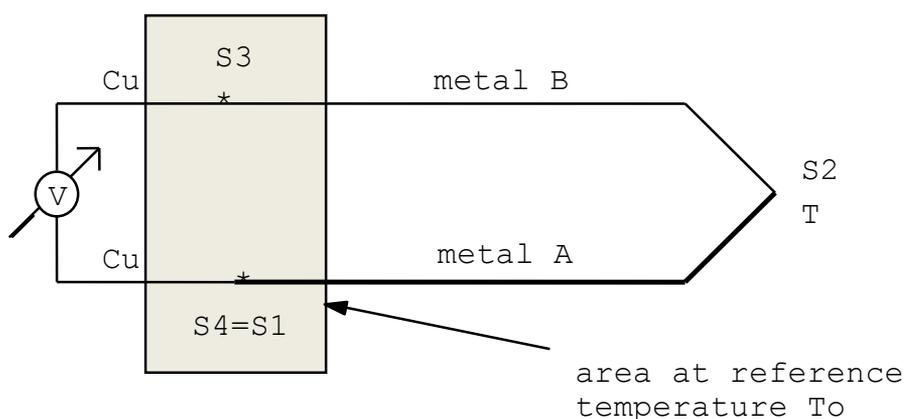


Figure 5 : Improved thermocouple setup

### III.5 Gas thermometer

The schematic diagram of a gas thermometer at constant volume is shown in fig. 6. The gas is trapped in a container B that is linked to a column of mercury through a capillary. The volume of gas is held constant by adjusting the height of the column  $M$ , until the mercury reaches a precise point. This height  $M$  is adjusted by moving the mercury container (or adjusting the pressure). The principle of this temperature measurement is pretty simple:

Measure the height  $h_0$ , when B is in contact with the triple point of water (or any other reference temperature) and  $h$  when B is in contact with the system to measure.

In the setup you will use, the thermometer is made of a tube of 2.7 mm interior diameter and 475 mm long. The volume of gas contained at the bottom of the tube is indicated by a drop of mercury.  $T_0$  take a temperature measurement, simply adjust the pressure in the tube using the pump, until the drop of mercury is aligned with the bottom of a ruler attached to the tube. Once the drop is aligned, simply measure the height  $\Delta h$  of mercury to find the pressure differential, and calculate the temperature.

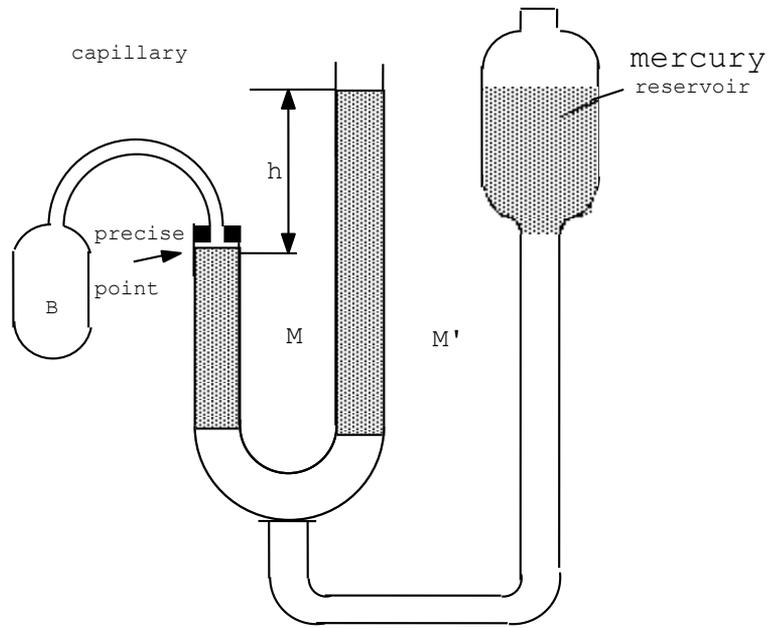


Figure 6 : Principle of a gas thermometer

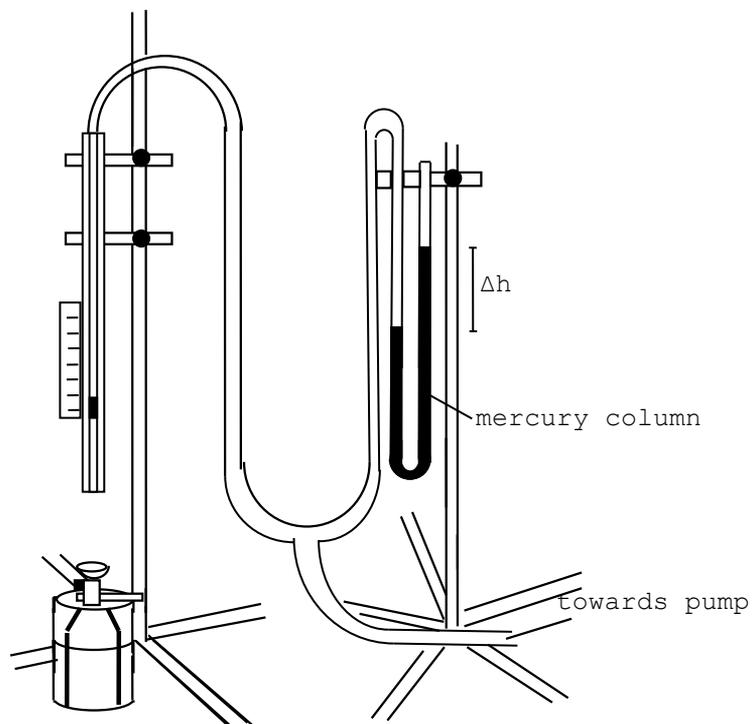


Figure 7 : Simplified setup of a gas thermometer

**Pros:**

- Legal measure of temperature

**Cons :**

- Long and complicated procedure

### III.6 Optical Pyrometer

We know that when heating a body sufficiently, it turns dark red: this color starts to appear around 500 °C. It turns red around 700 °C, orange around 1100 °C, and gets closer to white around 1300 °C. This effect can be used to measure the temperature.

Disappearing filament pyrometers are made of an objective, pointed towards the object to measure, to get an image on which it superimposes a heating filament. The filament is heated until it is the same color as the background (thus disappearing), at which point it will have reached the same temperature as the object.

This process can be made easier when watching the whole scene through a red filter, that only lets a selected spectral band go through.

## IV. TRAVAIL DEMANDE

**a)** Measure a **platinum probe 100Ω (Pt100)** resistance, using a 4 wire setup (two wires bringing the current, and two measuring the voltage).

Verify the following behavior:

$$R = R_0(1 + \alpha T) \quad \text{avec } T \text{ en } \text{[C]}$$

$$R_0 = 100\Omega \quad \text{et} \quad \alpha = 0.00385 \text{ [C}^{-1}\text{]}$$

**b)** Calibration of a chromel-alumel thermocouple (fusion temperature 1453 [C]). As a reference temperature  $T_0$ , use either the air temperature, or better, ice water. Then, measure the thermoelectric voltages for different temperatures. Compare these voltages  $\mathcal{E}(T - T_0)$  with results in the reference tables.

Make sure these measures can be reproduced.

**c) Gas thermometer:** calibrate the thermometer, assuming an gas is ideal.

Comment on this hypothesis validity.

**d) Pyrometer:** Measure the temperature of an oven from a distance, using a disappearing filament pyrometer. Compare the obtained results with those of a thermocouple placed directly in the oven (temperature range 600 [C to 1200 [C).

### Experimental Procedure

**Platinum Probe:** Connect the platinum probe to the current source and both multimeters as indicated (fig. 8). Fill the pan with water, and start heating. Place the platinum probe and the alcohol thermometer in the pan. Make sure you measure the temperature of the water, and not that of the bottom of the pan. (fig. 9)

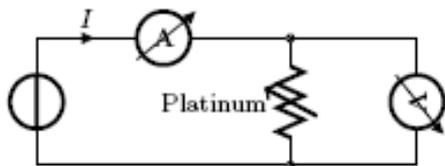


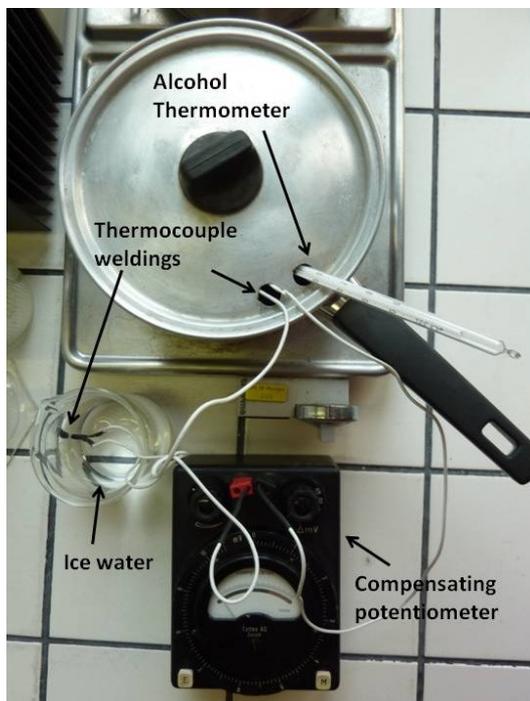
Fig. 8 : Diagram of the platinum probe's electric connections



Fig. 9 : Measure using the platinum probe

**Thermocouple:** Place one end of the thermocouple in ice water, and the other in the pan along with the alcohol thermometer (fig. 10). Measure the temperature of the thermocouple using a compensating potentiometer. Here are instructions on using it:

- 1) Place the voltage selection button (right) on 0 mV .
- 2) While keeping the E button pushed down, move the continuous tuning button (left) until the pointer indicates the red E marker (work voltage of the measuring bridge). Release the button.
- 3) Connect the thermocouples to the + and – terminals. Keep the M button pushed down, and turn the mV scaled ring until the pointer is back to 0. The number indicated by the triangle is the thermoelectric voltage.
- 4) Once you're done, don't forget to turn the right selection button back to OFF.



Once again, calibrate the thermometer using the alcohol thermometer as a basis, and make sure you are measuring the temperature of the water rather than the bottom of the pan. Compare the result with those found in the reference tables.

Fig 10 : Image de la mesure avec thermocouple.

**Gas thermometer:** As was already explained, we want to change the gas' pressure in order to keep a constant volume after the temperature variation. Place the whole gas (i.e. end of the tube + ruler, see fig. 11) in a graduated cylinder filled with water, and adjust the pressure in order to bring the drop of mercury back to its starting point (ideally, the bottom of the ruler). Then, measure the temperature of the gas.

In practice, since it is hard to heat the water once it is in the graduated cylinder, it is easier to fill the cylinder with boiling water, and take measurements as the water cools.

**Pyrometer:** Heat the target using the power supply (do not exceed 70 V ). Adjust the temperature of the pyrometer in order to make the filament disappear in front of the target. Take measurements between 700  $^{\circ}\text{C}$  and 1000  $^{\circ}\text{C}$ . (Fig. 12)

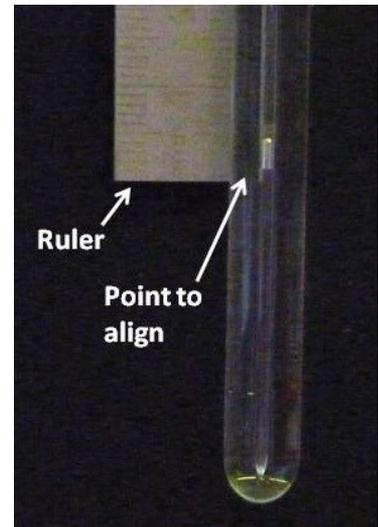


Fig 11.: Thermomètre à gaz

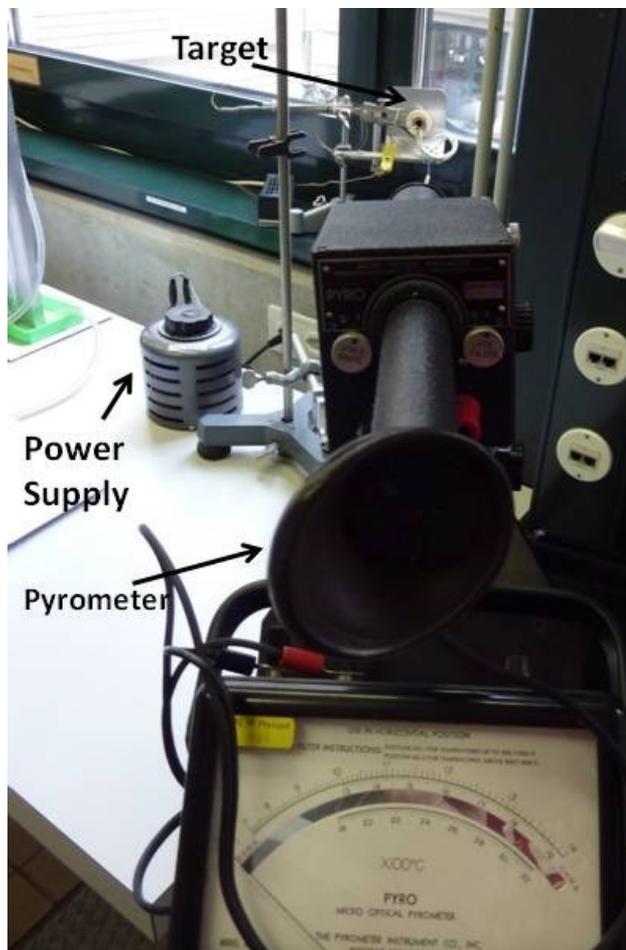


Fig 12: Pyrometer