INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE [illegible] TELEFAX [illegible] TELEX [illegible]

SMR/543 - 8

EXPERIMENTAL WORKSHOP ON
HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS
(BASIC ACTIVITIES)

(11 February - 1 March 1991)

" Temperature Control and Appendixes" "

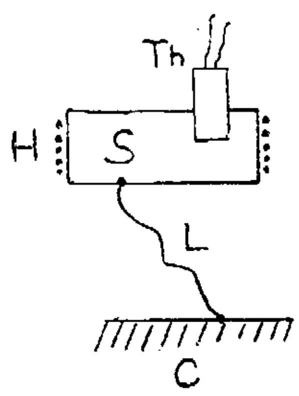
presented by:

M. DURIEUX
Leiden University
Kamerlingh Onnes Laboratory
P.O. Box 9506
Nieuwsteeg 18
2300 RA Leiden
Netherlands

Temperature Control

The automatic control of a system in order that it stays in a certain desired state has many applications. The desired state can be a state of constant position or pressure or temperature etc, or of a programmed change in time of such parameters. Here we will only make a few remarks distinguishing between Proportional, Integral and Differential Control.

Let us consider a system S at temperature T with a heater H and thermometer Th, which is connected to a cold reservoir C by a heat link L and let us assume that we want to keep the system S at a constant temperature T_0, higher than that of the cold reservoir C. (Often the heater can more efficiently be placed where the heat link joins the system). Let us further assume for definiteness that the thermometer gives a DC voltage signal, the value of which increases as T decreases (eg. the voltage of a diode thermometer or the voltage over a carbon resistance thermometer at constant current).



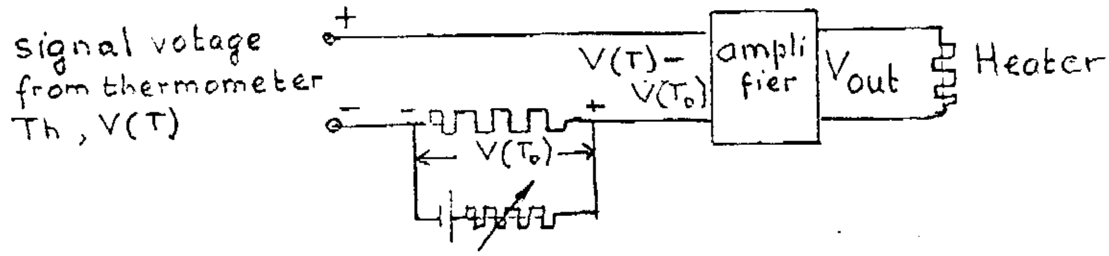
1.Proportional Temperature Control

One subtracts from the signal voltage V(T) an external voltage $V(T_0)$ corresponding to the signal voltage which the thermometer would give at the desired temperature T_0 and one uses the voltage difference $V(T)-V(T_0)$ as input for a proportional amplifier. The output voltage of the amplifier $V_{out} \propto [V(T)-V(T_0)]$ is then used as a source for the heater current I_H. If we assume that over the range T to T_0 V(T) is proportional with T we obtain

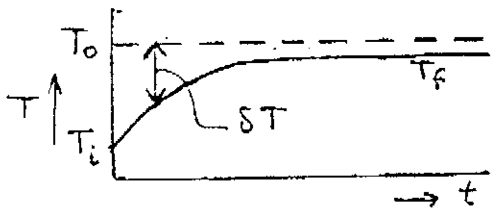
$$I_H = ß_p(T-T_0)$$

i.e. the heater current is proportional to the <u>deviation of the system's actual temperature T from the desired temperature T_0</u>.

The electrical circuit for temperature control at temperature T_0 can be as follows:



If the system is initially at a temperature $T_i<T_0$ its temperature will change in time as shown in the following graph:



The heater current, which is proportional to δT, will decrease until the system reaches a final equilibrium temperature T_f.

There are two disadvantages of Proportional Control:

a. The system will never reach T_0 (because then the current would be zero)

b. If the heat leak to the cold reservoir changes (eg. increase due to bad vacuum) the heater current has to becomelarger and this can only happen if δT is larger: thus the final equilibrium temperature will depend on the size of the heat leak.

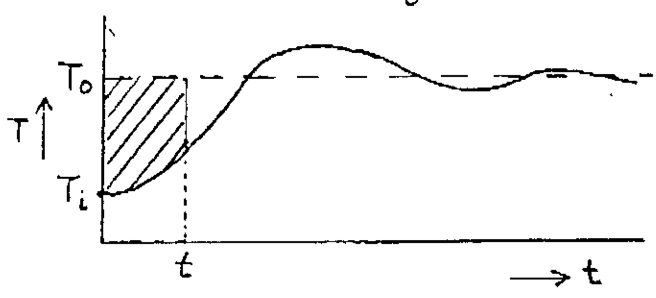
2. Integral Control

In this case one uses an integrating amplifier so that its output voltage is given by the relation:

$$V_{out}(T) = \alpha_i \int_0^t [V(T)-V(T_0)]\, dt$$

and, consequently, the heater current will be

$$I_H = \beta_i \int_0^t (T-T_0)\, dt$$



The system's temperature will now evolve in time as sketched in the figure. At a time t the heater current is proportional to the shaded area. Conse-

quently, the current will reach a maximum when T reaches T_0 and will only then start to decrease. The temperature will oscillate slowly to the desired temperature T_0.
The advantage of this integral control is that the system can never deviate for a long time from T_0; a disadvantage is that there is a tendency for the temperature to oscillate around T_0.

3. Differential Control
In this case an amplifier is used which gives as output

$$V_{out}(T) \simeq \alpha_d \frac{d\left[V(T)-V(T_0)\right]}{dt} \simeq \alpha_d \frac{dV(T)}{dt} \qquad \alpha_d < 0$$

and, consequently

$$I_H = \beta_d \frac{dT}{dt} \qquad \beta_d < 0$$

This type of control will obviously try to prevent oscillations of the system.

4. P I D - control
In general one combines the three types of amplification in one amplifier so that

$$I_H = \beta_p (T-T_0) + \beta_i \int_0^t (T-T_0)\,dt + \beta_d \frac{dT}{dt}$$

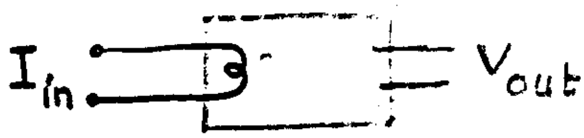
β_p, β_i and β_d can then be changed independently. Experimentally or, if one knows all parameters of the system, by solving the differential equation, one can find the best choice of β_p, β_i, and β_d for most suitable control.

At very low temperatures one often uses only proportional control and diminishes the before mentioned disadvantages by using high amplification. If eg. T_0-T_f is only 10 mK, T_f will not change by more than 2*10 mK unless the heat loss will change by more than a factor of two.

For complicated systems one tries to solve the equations and calculate best values for β_p, β_i and β_d. For example we heard that Shell Oil Company made extensive calculations for controlling the spatial position of oil-drilling equipment at sea.

Appendix 1

Principle of the SQUID (Superconducting Quantum Interferometric Device)



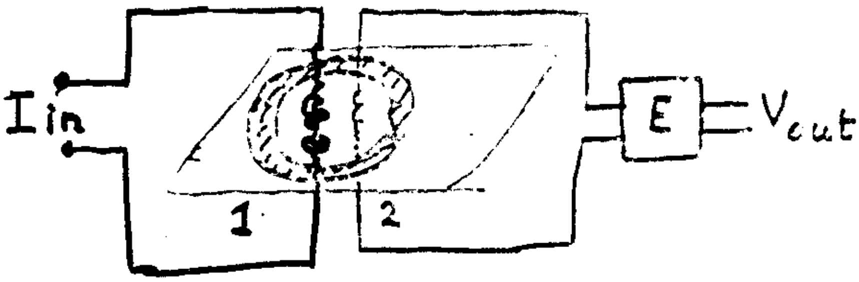
$V_{out} \approx F\, I \frac{\text{volt}}{\text{ampere}}$

input $R = 0$
$L \approx 2\,\mu H$

very low currents $\sim 10^{-11}$ A can be detected

R 

or over a low resistance very small voltages can be detected e.g. $R \approx 10^{-4}\,\Omega$. voltages of $\sim 10^{-15}$ volt

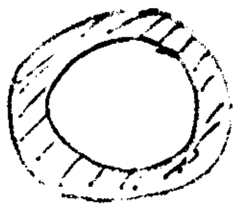


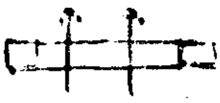
a superconducting ring with a weak contact (Josephson junction)

A small input coil[1] goes perpendicular through the ring. A second coil[2] through the ring senses the current changes in the input coil. Electronics (E) takes care for an output voltage $V_{out} \propto I_{in}$

How does it work ?

Appendix 2





The total magnetic flux through a closed superconducting ring

$$\phi = \iint B \, dA \qquad A = \text{area}$$

is quantized

$$\phi = n\,\phi_o \quad \text{with}$$

$$\phi_o = \frac{h}{2e} = 2 \cdot 10^{-15}\ \mathrm{T\,m^2}$$

and will not change even if one introduces a flux through the ring using a perpendicular input coil. Compensating supercurrents in the ring will counteract the flux which is brought in

If one interrupts the ring with a "weak contact one can limit the maximum possible supercurrent in the ring to a very small value

If one now "slowly" brings in a flux through a "slowly" varying input current through the input coil, the supercurrent still will keep the total flux in the ring equal to a whole number of fluxquanta ϕ_o but cannot prevent that n (in $\phi = n\phi_o$) increases Fluxquanta ϕ_o will "jump" into the ring. This is detected by the second coil through the ring. The electronics will register this with a sensitivity of $10^{-5}\,\phi_o$

What is the current sensitivity ?

$$\Delta I_{input} \Rightarrow \Delta\phi = \Delta I_{input} M$$

M = mutual inductance between the input coil and the ring

typically $M \approx 2\,\mathrm{nH}$

$$\Delta I_{input} = \frac{10^{-5} \cdot 2 \cdot 10^{-15}}{2 \cdot 10^{-9}}\,A = 10^{-11}\,A$$

minimum detectable

over a resistance of $0.01\,\Omega$ this corresponds to 10^{-13} volt