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Institut für Reaktorentwicklung

**Combined Thermocouple-Noise
Thermometry**

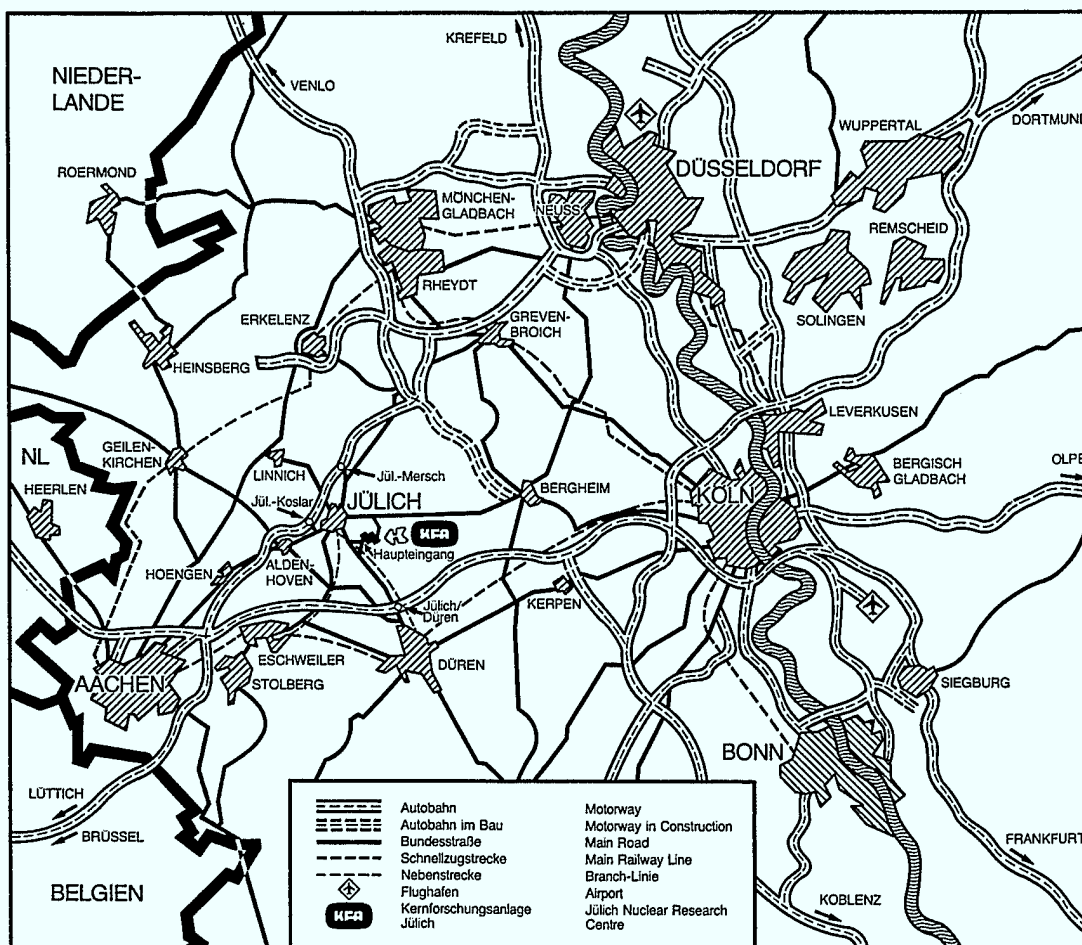
by

H. Brixy

Jül - 2051 (trans)

April 1986

ISSN 0366-0855



Als Manuskript gedruckt

Berichte der Kernforschungsanlage Jülich – Nr. 2051 (trans)

Institut für Reaktorentwicklung Jül - 2051 (trans)

Zu beziehen durch: ZENTRALBIBLIOTHEK der Kernforschungsanlage Jülich GmbH

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H. Brixy

Revised version of a lecture held at the VDI Seminar
"Techniques of Measuring High Temperatures",
March 1984, Düsseldorf (BW 6031)

COMBINED THERMOCOUPLE-NOISE THERMOMETRY

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H. Brixy

ABSTRACT

The combined thermocouple-noise thermometer (TC-NT) unites the advantages of the thermocouple (simple measuring procedure, high sensitivity) with those of the noise thermometer (no de-calibration, high absolute accuracy).

With the combined thermometer, the TC in the sensor can be calibrated in situ. The advantage of this in situ calibration is that also all parasitic thermovoltages from inhomogeneous thermocouple wires in temperature gradients are calibrated and thus no measurement error arises.

With the combined thermometer it is now possible for the first time to detect and eliminate in practice inhomogeneity errors (drifts).

In order to clarify understanding of the basic effects, the modern theory of the thermocouple (generation of thermovoltage in the wires only in temperature gradients) is described as well as the principles of noise thermometry.

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A THERMOCOUPLES

1. INTRODUCTION

There is a general problem in measuring high temperatures with contact thermometers in that the measuring sensor itself is changed by the temperature, i.e. the ambient effects due to the high temperature change the measured quantity used in the sensor in an unforeseen and uncontrollable manner. The ambient effects are generally combined in such a complex manner that the temperature can no longer, or only with difficulty, be determined. In practice this means that the temperature characteristics of the sensor are changed and that both the operating range and time are limited by this drift.

This is especially also true of the thermocouples frequently used in measuring temperatures in the high-temperature range.

Apart from effects induced by high temperatures, the e.m.f. of the thermocouples (thermovoltage) is also altered by high pressure, high magnetic fields and high radiation. For example, a neutron flux of $10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ for six months is sufficient to convert by transmutations 20 % of the rhodium of a PtRh/Pt thermocouple into palladium, which can even reverse the polarity of the thermocouple.

Accurate temperature measurements, reliable even after prolonged operating times, are therefore not possible under such conditions with conventional thermocouples.

2. THERMOCOUPLES AT HIGH TEMPERATURES

In using thermocouples (TC) with the aid of standard reference tables (listing the relationship between the voltage displayed and the temperature difference of the junctions) the laws for an ideal TC are assumed, i.e. for a TC with physically and chemically completely homogeneous wires. However, in practice it becomes apparent when using TC's that more or less large inhomogeneities of the thermocouple wires must always be expected which are already present in the wires as received and which

can be considerably increased depending on operating conditions and operating time. This then leads to "inhomogeneity" errors expressed as deviations from the nominal values of the e.m.f.

At higher temperatures the inhomogeneities are caused by the temperature itself (diffusion phenomena: impurities from the surrounding atmosphere and the insulation, exchange of the alloying elements, recrystallization, phase transformations, preferential evaporation of a component etc.).

The extent depends on the time, temperature, atmosphere, wire size and other geometric dimensions.

Furthermore, the e.m.f. also depends on the mechanical and thermal pretreatment.

An example of the e.m.f. drift is given by studies on TC's installed in the top reflector of the AVR reactor, a high-temperature reactor at Jülich, examined after removal:

type: NiCr/Ni;	operating time: 2 years for TC 1,
diameter: 3 mm;	8 months for TC's 2,4,7;
sheath: Inconel 600;	temperature: up to 1000°C
insulation material: MgO	

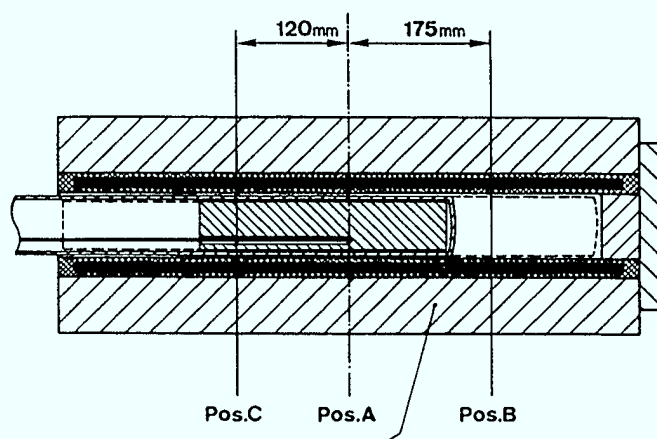


Fig. 1: Experimental arrangement for "recalibration"

The TC's were examined in a furnace at 3 different positions (A, B, C, Fig. 1) in order to determine locally differing inhomogeneities by varying the temperature gradient along the TC wires.

The results are shown in Fig. 2. Depending on the position of the temperature gradient, positive or negative deviations are obtained with respect to the different inhomogeneities. The figures thus show that the inhomogeneities along the TC and the temperature gradient during the respective measurement are of decisive importance. On the other hand, this means that quantitative statements about measuring errors are only possible in retrospect if during "recalibration" the same temperature gradients are present as before in the plant. Since the temperature gradient along the TC is generally not precisely known, and moreover the simulation of gradients during "recalibration" could only be realized at great effort, previous measurement errors cannot be determined by "recalibrating" the thermocouples. The maximum possible errors can only be specified if during "recalibration" all possibilities are realized with respect to the temperature distribution along the TC wires. It furthermore follows that the size of the measurement errors varies during operation if the temperature profiles are altered.

The change in the e.m.f. of the thermocouples was caused here by material changes in the thermocouple wires as a consequence of the high operating temperature and the surrounding atmosphere (diffusion, recrystallization, corrosion etc.). In this case, reactor radiation was not significant.

3. THE MODERN THEORY OF THERMOCOUPLES

The modern theory of thermoelectricity developed within the framework of solid-state physics has contributed towards understanding the described effects /1,2/.

The thermoelectric voltage is generated in the TC wires only in the temperature gradient /3,4,5,6,6*/ and not, as described in older concepts still widespread today in many textbooks,

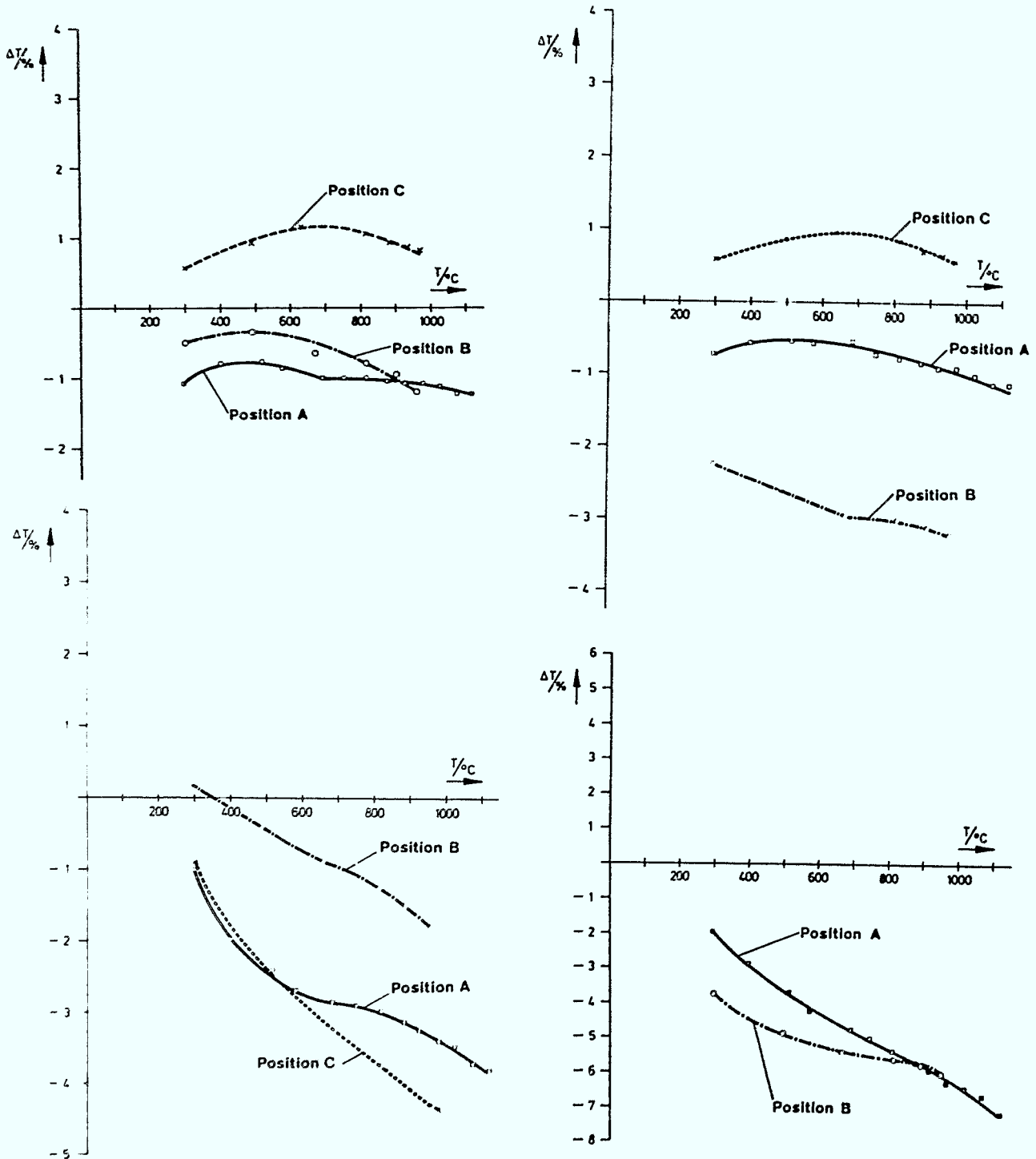


Fig. 2: "Recalibration" of AVR thermocouples a) TC 2 b) TC 4
c) TC 7 d) TC 1

in the hot and cold junctions or partly in the junctions and partly in the temperature gradient. As a result of these misunderstandings concerning the generation and causes of thermovoltages, serious mistakes were and still are made in the calibration and in the utilization of TC's.

a) Ideal and Real Thermocouple

Figs. 3 and 4 show the generation of the thermovoltage in the temperature field.

$e(T)$ is the absolute thermoelectric power (absolute Seebeck coefficient) of a homogeneous conductor which does not depend on the position on the conductor but only on the absolute temperature and which is specific for the conductor material under consideration. The thermovoltage is generated by the temperature gradient; it is therefore only formed where the temperature varies; this is shown in the equivalent circuit diagram (if the e.m.f. is measured by an instrument with a high input and the insulation resistances between the wires and to ground are high, then the series resistances are of no significance).

Only the electric circuit is closed by connecting the two thermowires at the hot junction and thus the potential difference $E_A - E_B$ can be measured at the terminals in the cold range.

In the case of ideal TC's the result (the thermovoltage E_{AB}) agrees purely formally with the old concept, as shown by the second and third integral in Fig. 3. If the absolute thermopower only depends on the temperature then the thermovoltage E_{AB} only depends on the temperatures of the junctions. This would be the desired function of a thermocouple. Nevertheless, it still remains true that the thermovoltage arises in the temperature gradient.

The situation is quite different with a real TC with not completely homogeneous wires. Due to the inhomogeneities, an additional term $\delta e(T,s)$ is given here as a function of the absolute temperature and of the position (the variation in thermopower $e(T)$). The integral in Fig. 4 is thus position-dependent. In this case the position, the path of the thermowires in the temperature profile is decisive. If the

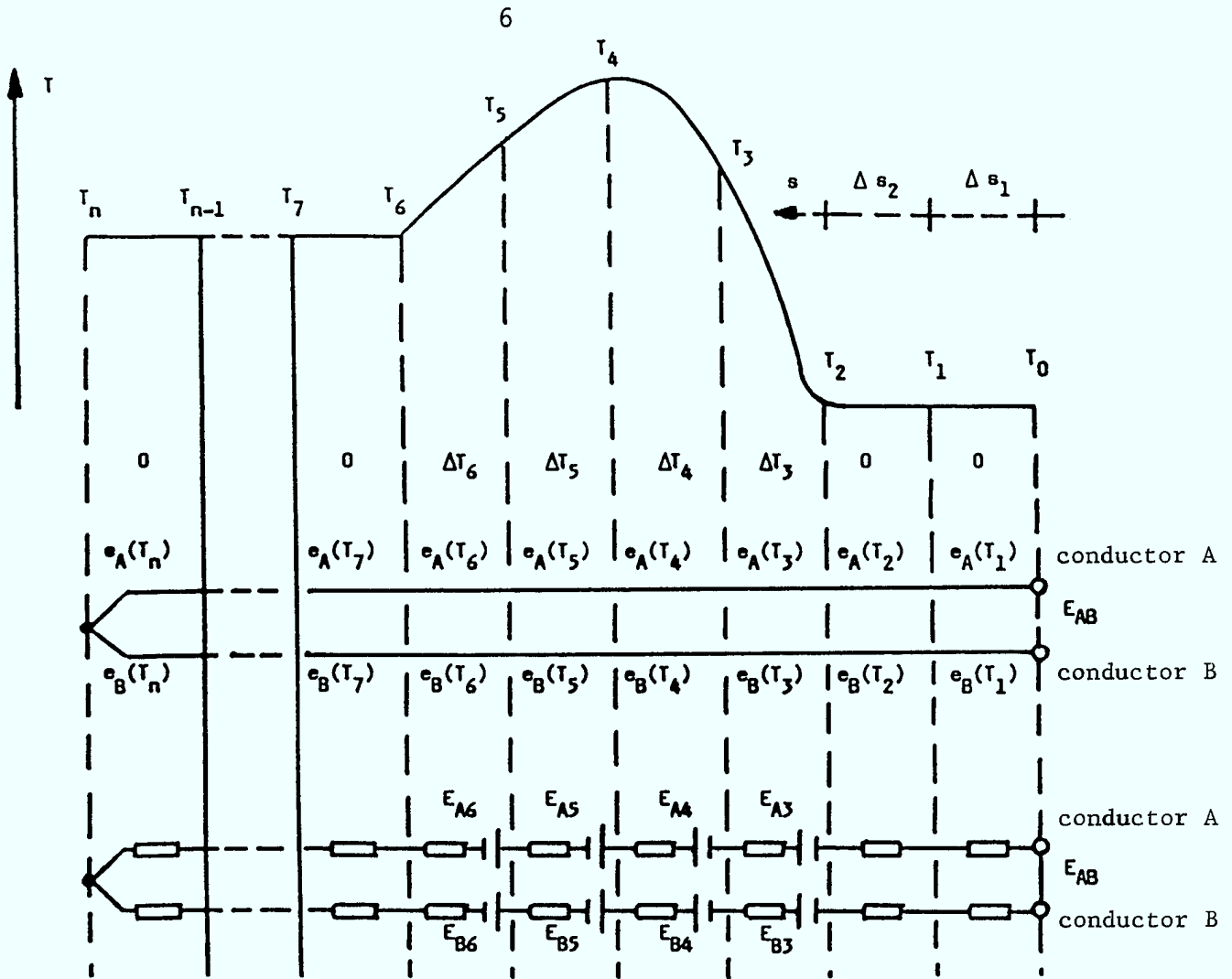


Fig. 3: Ideal thermocouple in a temperature profile with equivalent circuit diagram

$e(T)$ absolute thermopower (thermoelectric power) of a homogeneous conductor (absolute Seebeck coefficient)

$E_{An} = e_A(T_n) \cdot \Delta T_n$ absolute thermovoltage (thermoelectric voltage) of conductor A in Δs_n

$\sum_n E_{An} = E_A$ absolute thermovoltage of conductor A

$E_A - E_B = E_{AB}$ thermovoltage between conductor A and B (emf of TC)

$e_A(T) - e_B(T) = e_{AB}(T)$ (relative) thermopower between conductor A and B (relative Seebeck coefficient)

$$\int_0^n \left[e_A(T) - e_B(T) \right] \cdot \frac{dT}{ds} \cdot ds = \int_{T_0}^{T_n} \left[e_A(T) - e_B(T) \right] \cdot dT = \int_{T_0}^{T_n} e_{AB}(T) dT = E_{AB} \quad (1)$$

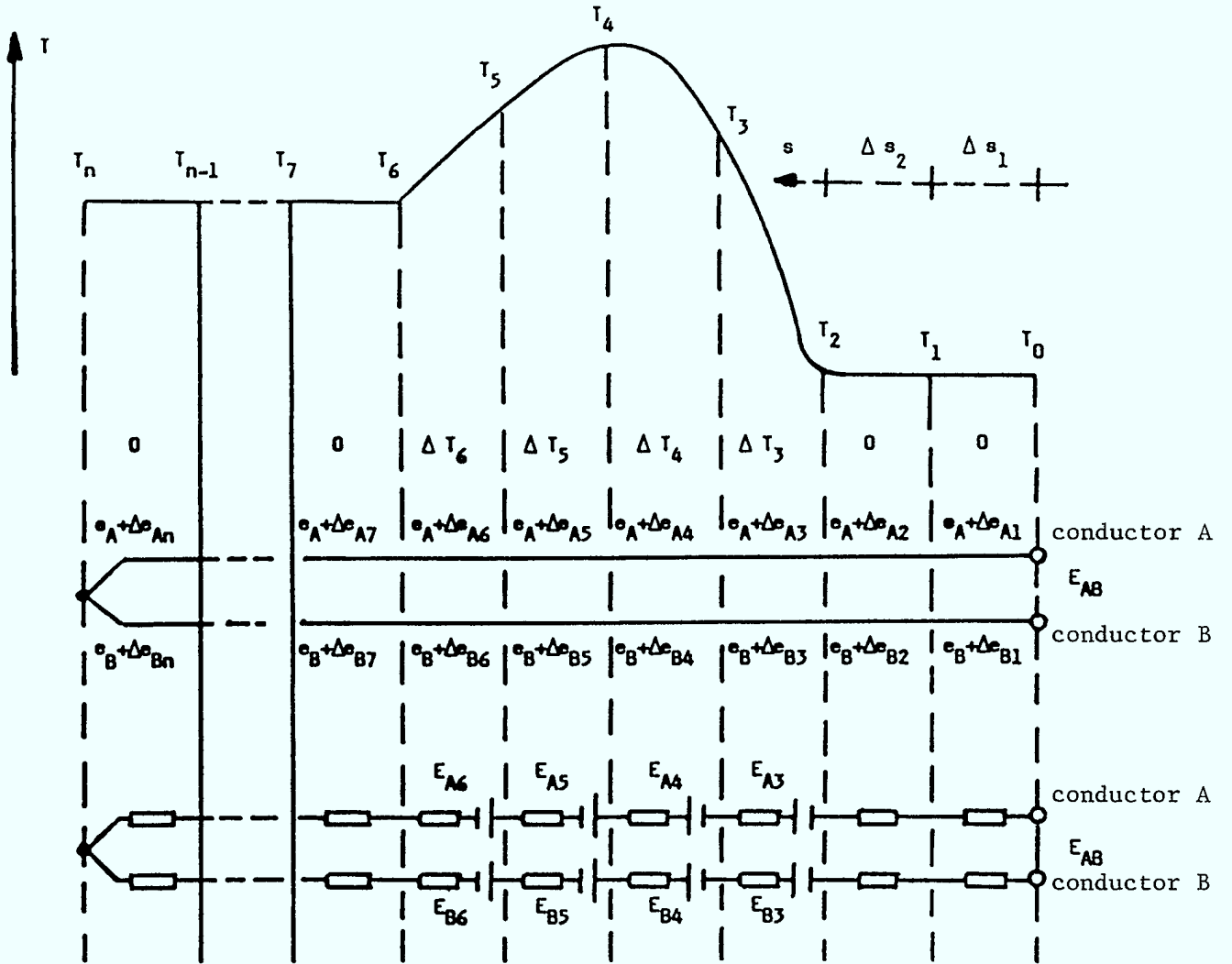


Fig. 4: Real thermocouple in a temperature profile with equivalent circuit diagram

$e(T)$ absolute thermopower of a homogeneous conductor

$\delta e(T, s)$ variation of the absolute thermopower

$E_{An} = [e_A(T_n) + \Delta e_{An}(T_n)] \cdot \Delta T_n$ absolute thermopower of conductor A in Δs_n

$\sum_n (E_{An} - E_{Bn}) = E_{AB}$ thermovoltage between conductor A and B (emf of TC)

$$\int_0^{s_n} [e_A(T) + \delta e_A(T, s) - e_B(T) - \delta e_B(T, s)] \cdot \frac{dT}{ds} \cdot ds = \int_0^{s_n} [e_{AB}(T) + \delta e_{AB}(T, s)] \cdot \text{grad} T \cdot ds =$$

$$= \int_0^{s_n} e_{AB}^*(T, s) \cdot \text{grad} T \cdot ds = E_{AB} \quad (2)$$

$$\delta e_{AB}(T, s) = \delta e_A(T, s) - \delta e_B(T, s)$$

$$e_{AB}^*(T, s) = e_{AB}(T) + \delta e_{AB}(T, s)$$

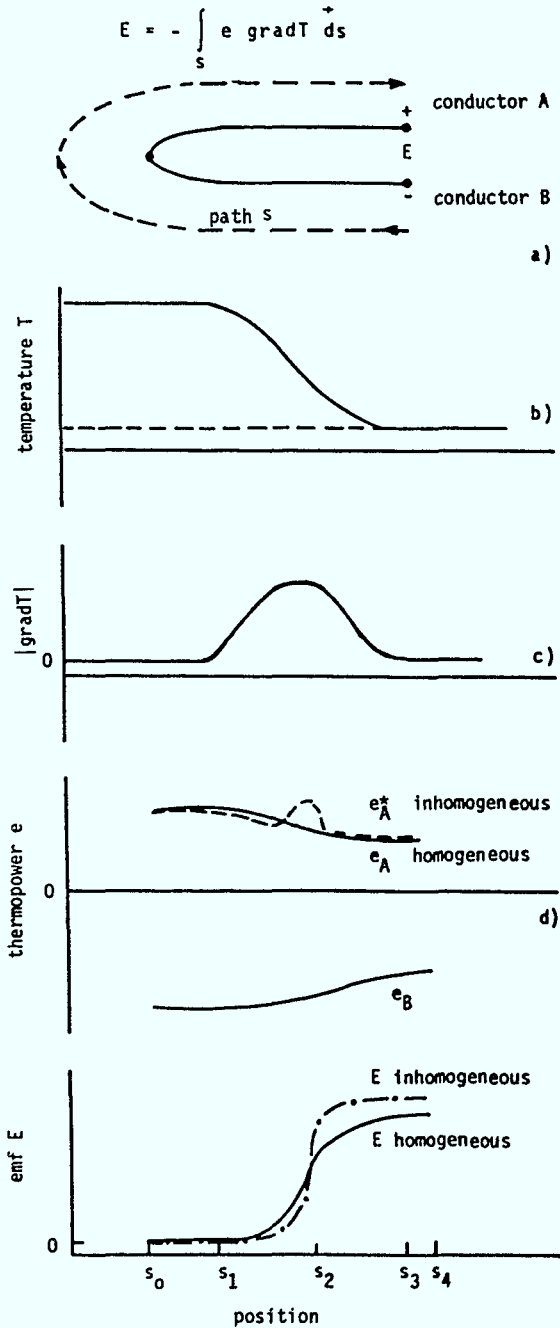


Fig. 5: Effects of temperature gradient and inhomogeneities on the thermal e.m.f. of a thermocouple

position varies, i.e. if the temperature gradient along the thermowire varies, then the measured voltage varies, even if the temperatures of the hot and cold junction remain constant.

The term $\delta e(T, s)$ describing the drift of the e.m.f. can in unfavourable cases reach the order of magnitude of the original thermopower $e(T)$.

Fig. 5 /7/ gives a schematic illustration of Eq. (2) in Fig. 4. The TC (Fig. 5a) is in a temperature profile as shown in Fig. 5b. Fig. 5c shows the absolute value of the associated temperature gradient. Fig. 5d gives an arbitrary (but possible) shape of the absolute thermopower which is generally only slightly temperature-dependent; namely, a positive thermopower for a homogeneous conductor A and a negative thermopower for a homogeneous conductor B, as is usually combined. The course of the thermopower with an inhomogeneity at position s_2 is additionally indicated for conductor A by a dotted line.

Fig. 5e shows the structure of the e.m.f. for the homogeneous and inhomogeneous case. Since the inhomogeneity is located in the temperature gradient, a different total thermovoltage from the homogeneous case is obtained. Only if the inhomogeneity were located outside

the temperature gradient would the same thermovoltage arise as in the homogeneous case.

The fundamental difference in the operating principle of a thermocouple and a resistance thermometer can be seen in Figs. 3-5. The resistance thermometer shows the temperature of the resistor itself, i.e. the temperature of the sensor tip; the conductors (4-wire technique) through the temperature gradient are in general of no significance. In a thermocouple, on the other hand, the voltage arising in the temperature gradient along the thermowires is added up and serves as a measure for the temperature difference between the hot and cold junction.

b) On Understanding Thermovoltage by the Electron Theory

Qualitatively, thermoelectricity is well understood today. The precise physical explanation and the computation of thermoelectric effects by solid-state physics is however extremely complex /1,2/. Thus, for example, it is still not possible to predict the thermovoltage of metals and alloys with adequate precision. The TC tables used in practice are therefore empirical relations between temperature differences and e.m.f..

The generation of the thermovoltage can be illustrated - at least in a rough qualitative manner - by the simple model of free electron gas. If an insulated conductor is heated at one end then the electrons in this hot end have a higher mean velocity than the electrons in the cold end. Some of the electrons therefore diffuse from the hot to the cold end and a continuously changing electron density occurs along the temperature gradient. A voltage therefore builds up in the temperature gradient between the hot and cold end. The magnitude of this voltage depends on the absolute temperatures of the two ends and on the material of the conductor. If two conductors made of different materials are arranged parallel to each other in the same temperature gradient then different voltages arise and this difference is measured as the e.m.f. of the thermocouple.

This simple model illustrates that the electron density varies in the temperature gradient, that is to say the temperature gradient is the driving force for the generation of an electric field: $\mathcal{E} = e \cdot \text{grad } T$.

A precise analysis of the thermoelectric effect confirms the statement of the simple electron gas model with respect to the generation of the thermovoltage in the temperature gradient /8,1,2/. However, this simple model is not suitable for more detailed statements; the model thus results in a negative thermopower (accumulation of negative charge at the cold end) as displayed e.g. by Pt. The positive thermopower (excess electrons at the hot end) of metals such as Ag, Cu, Au cannot, however, be explained. To this end and to compute the magnitude of the thermovoltage, the scattering interactions of the electrons in the temperature gradient in a special metal lattice must be precisely known.

The electron theory provides an expression for temperatures above the Debye temperature ($T > 300$ K for most metals and alloys) which reproduces at least approximately the measured absolute thermopower for nontransition metals:

$$e_d = - \frac{\pi^2 k^2 T}{3 e_0} \left(\frac{\delta \ln \sigma(\epsilon)}{\delta \epsilon} \right)_{\epsilon=\epsilon_F} \quad (3)$$

(e_d diffusion thermopower; k Boltzmann constant; e_0 elementary charge; σ conductivity; ϵ energy; ϵ_F Fermi energy.)

(In addition to e_d a further term e_g , the so-called phonon-drag thermopower, must be taken into consideration at low temperatures.)

$\sigma(\epsilon)$ can be written as a function of the mean free path of the electrons $l(\epsilon)$ and the Fermi surface $S_F(\epsilon)$:

$$\sigma(\epsilon) = \left(\frac{e_0^2}{12\pi^3 \hbar} \right) \cdot l(\epsilon) S_F(\epsilon) \quad (4)$$

Both $l(\xi)$ and also $S_F(\xi)$, and thus the thermovoltage, depend on a number of parameters and external influences: on the metallurgical state and chemical composition as well as variations in these (short-range ordering effects, cold working, lattice defects, impurities etc.), on high pressure and high magnetic fields. The sensitive dependence of the thermovoltage on ambient conditions thus becomes theoretically comprehensible.

c) The Misunderstanding Contained in the Old Thermocouple Theory

According to the first law of thermodynamics, the following is obtained in a closed circuit of a thermocouple in the stationary state (see e.g. /9/):

$$\oint dU = \left[\pi_{AB}(T_n) - \pi_{AB}(T_o) - \int_{T_o}^{T_n} (\tau_A - \tau_B) dT - E_{AB}(T_n, T_o) \right] \cdot J \cdot t = 0$$

resulting in a relation between the thermovoltage E_{AB} (Seebeck effect), the Peltier coefficient π_{AB} and the Thomson coefficients τ_A, τ_B :

$$E_{AB}(T_n, T_o) = \pi_{AB}(T_n) - \pi_{AB}(T_o) - \int_{T_o}^{T_n} (\tau_A - \tau_B) dT \quad (5)$$

(U internal energy; T_n, T_o see Figs. 3 and 4; J current in the circuit; t time.)

It was concluded from Equation (5) that the thermovoltage is composed of four fractions: of voltages arising at the junctions ($\pi_{AB}(T_n)$ and $\pi_{AB}(T_o)$) as well as of voltages arising in the wires in the temperature gradient ($\int \tau_A dT$ and $\int \tau_B dT$), the major portion of the total thermovoltage being generally allocated to the junctions. So equation (5) was taken as the defining equation for the thermovoltage and for the position where the thermovoltage was generated.

However, Equation (5) only gives a mathematical connection between the Seebeck, Peltier and Thomson effects during current flow in a closed circuit if different materials are present in a temperature gradient (i.e. under quite specific conditions); this connection does not make any statement about the causes and position of generation of the thermovoltage.

The thermovoltage is measured with an open circuit, i.e. at current $J = 0$; under these circumstances neither the Peltier nor the Thomson effect exist since they are pure current effects.

On the other hand, during current flow the Peltier effect can occur in an isothermal circuit and the Thomson effect in a circuit with a single homogeneous material, although in both cases the thermovoltage is zero.

4. THERMOCOUPLES IN OPERATION

An example of the behaviour and possible errors of TC's in operation for prolonged periods is shown in Fig. 6. These are the results of an experiment with NiCr/Ni TC (diameter: 6 mm; sheath: Inconel 600; insulation: MgO) exposed for several weeks to temperatures of 1000/1100°C, and briefly to even higher temperatures (surrounding atmosphere: air).

During this period, the NiCr and Ni wires of the mineral insulated cable became inhomogeneous in the hot temperature range. The temperature profiles in which the inhomogeneities were generated were similar to the profile in Fig. 6a. The position of the TC is shown schematically with the tips (hot junctions) at the correct position in the profile.

The profiles were then changed by reducing the temperature in the individual zones; the position of the TC in the furnace remained constant (Fig. 6b, 6c, 6d). The deviations in the TC readings from the true temperature of the hot junctions are given in each case.

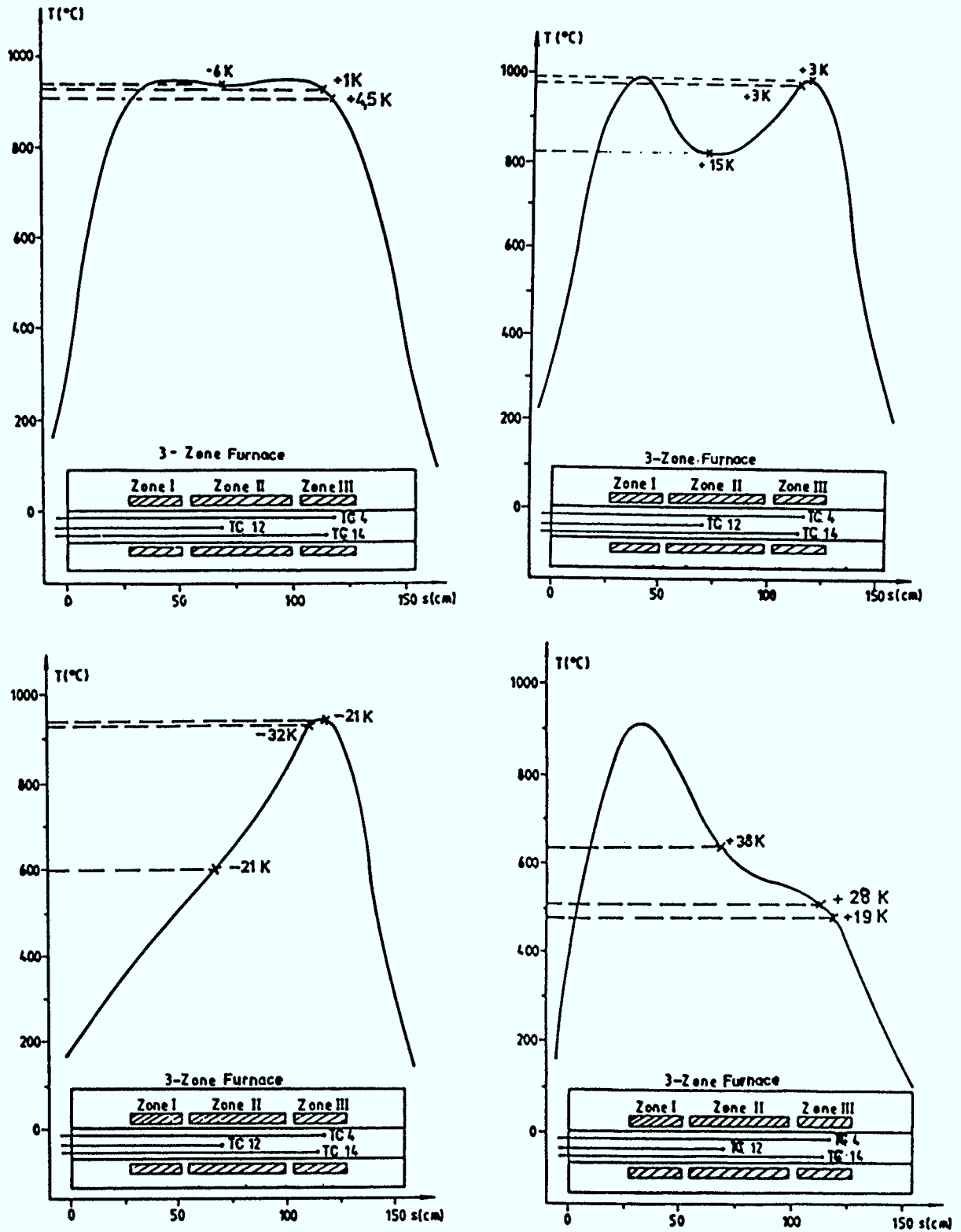


Fig. 6: Errors from inhomogeneous thermocouples in various temperature profiles

- a) normal profile at 950°C
- b) central zone lowered
- c) zone 1 and central zone lowered
- d) central zone and zone 3 lowered

These results show that depending on the temperature profile considerable positive and also negative errors can be obtained with one and the same TC (see also Fig. 2).

If there are variations in the temperature gradient along inhomogeneous thermowires - as in Fig. 6 by altering the temperature gradient with a constant position of the TC or with a constant temperature gradient by varying the position of the TC (e.g. by measuring a furnace profile; see also Fig. 1 and 2) - not even the sign of the measurement error is therefore generally known (exception: both the temperature profile as well as the nature of the inhomogeneities are known⁺). This fact has not yet been taken into adequate consideration.

The errors due to variation of the temperature gradient along the thermowires are known in the literature /10/ as errors of the second kind. These errors can take on large values even if the temperature of the measuring tip remains constant. Smaller errors are generally obtained if the position of the TC in the temperature gradient in which the inhomogeneities were generated does not vary. These are the so-called errors of the first kind. Both types of error have the same causes. A differentiation is meaningful because known drift errors in a TC at a fixed position and constant temperature profile cannot be used as a measure for the error of the same thermocouple in a different temperature profile.

a) Factors Changing the Thermopower

A list of the various factors and influences changing the thermopower and generating inhomogeneities is given in /11/ (see Table 1).

Diffusion and corrosion are of special significance at high temperatures; namely the higher the temperatures, the greater the significance.

⁺The positive and negative errors in Fig. 6 can be understood, if the thermopower in the hot range was reduced, as is normally the case under the conditions described.

Table 1: Summary of factors affecting the thermoelectric power.

a) Composition:

- 1) batch-to-batch variation in alloys
- 2) local variations in impurity, and alloy composition
- 3) absorption, by solution or chemical combination, of materials from the environment
- 4) loss of constituents by selective evaporation or chemical attack
- 5) solution of elements produced by nuclear transmutation

b) Metallurgical state:

- 1) work hardening, annealing
- 2) recrystallisation
- 3) solution/precipitation of constituents
- 4) ordering effects
- 5) dislocations (permanent or temporary) caused by nuclear radiation.

c) Physical forces:

- 1) elastic strain
- 2) static pressure
- 3) magnetic flux

b) The Short-Range Ordering Effect of NiCr/Ni-TC

However, temperature-induced inhomogeneities do not only occur at high temperatures but e.g. in the case of NiCr/Ni-TC even in the range of 200-600°C /11, 12, 13/. A short-range ordering effect arises in the NiCr leg enlarging the thermopower.

The rate of change and final value of the thermopower depend greatly on the temperature. The final value at 450°C is thus reached in a few minutes, whereas below 300°C only after several years.

The maximum drift occurs at approximately 300°C. The error can reach values of 1.1 % (according to /12/: 1.3 %) of the measured temperature.

The ordered state is destroyed above approximately 600°C; the effect is therefore reversible.

Fig. 7 (taken from /10,13/) gives an illustration of the ordering effect. The initial heating calibration curve A (deviations from the true temperature) already differs from

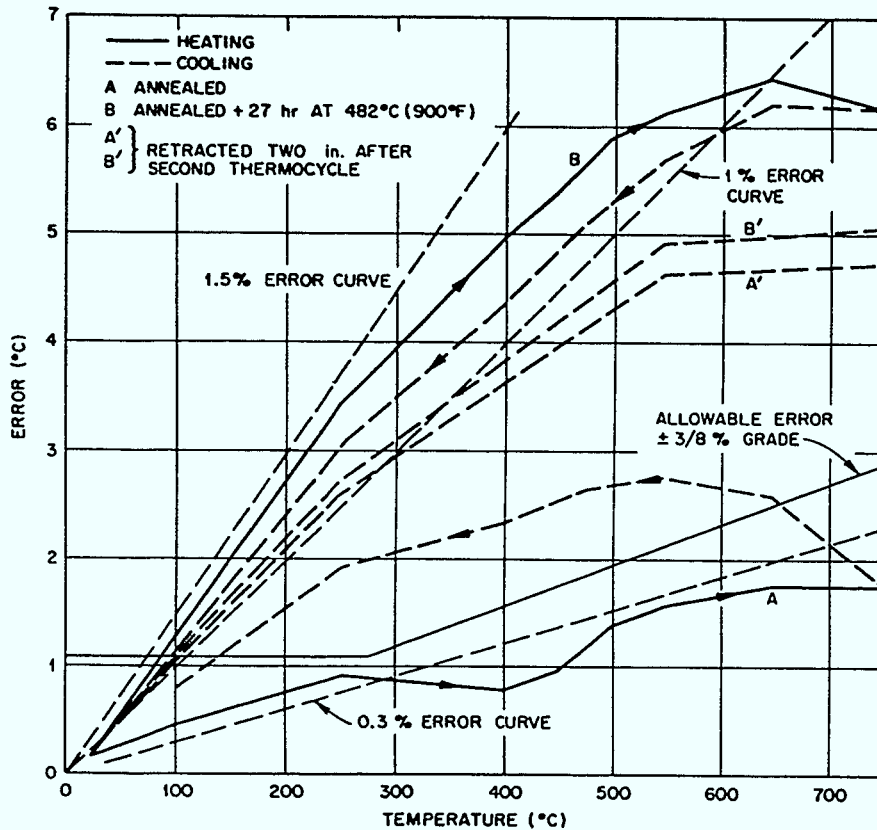


Fig. 7: Diagram of calibration data taken on heating and cooling an annealed and heat-treated NiCr/Ni-TC (from /13, 10/)

the cooling curve A (dotted) by up to 1.5 K (error of the first kind). A' shows the calibration curve of the same element after a change of position in the furnace (error of the second kind). The curves B, B' are analogously valid for a different TC "preordered" at 482°C.

These results clearly show that inhomogeneities are generated by the calibration method itself leading to greater errors of the second kind if the temperature profile along the TC during calibration is not the same as during later operation.

An uncertainty of approximately 5 K must therefore be taken into consideration for the NiCr/Ni-TC from the beginning, i.e. the usual tolerance (DIN, ASTM) can in general not be complied with (up to approx. 700-800°C).

Even in measuring temperatures above 600°C where the ordering effect does not exist, the critical zone (200-600°C) must be passed through, i.e. the ordering effect comes into full play.

c) Calibration, Recalibration, Drift Correction

Greater initial accuracies can be achieved with PtRh/Pt-TC and Nicrosil/Nisil-TC in the lower temperature range (up to approx. 1000°C). However, the TC's must be subjected to a special annealing process before their application in order to remove the effects of cold working etc. (for PtRh/Pt-TC e.g. up to 7 K /14/) /15, 12, 16/. At temperatures above 1000°C all TC's drift depending on the surrounding conditions and large errors, especially of the second kind, can result (/10/, Fig. 2,6).

Great efforts are frequently expended on experimentally determining, depending on time, the sign and magnitude of the thermovoltage drifts in order to be able to undertake corresponding corrections during later operational service. This presumes the same TC's (materials, fabrication etc.) and the same ambient conditions, as well as the same temperature profiles. The former can hardly be achieved in practice and the latter means that a large portion of the information to be obtained by the measurements must be input in advance in the form of assumptions. This type of method is not suitable for temperature measurements which have to be reliable. The same is analogously true of calibration, "before" and "after", often practised.

In general it can be said that it is not possible to recalibrate in the normal way a TC which has become inhomogeneous. The only possibility is a recalibration in situ (see Chap. C1) (with reference to meaningful homogeneity tests see /11, 7/).

Everything described so far refers to variations in the thermopower (the inhomogeneity errors), i.e. variation in the measured quantity of TC's per se. Distortions by other sources of error, such as electrical shunting, thermal shunting, electrical leakage and noise, as well as errors in the extension lead wires, reference junction, data acquisition system, have not been dealt with. For details see e.g. /17/.

The TC is therefore a sensor whose signal does not only, as is desirable, depend on the temperature, but on a number of parameters. Moreover, the TC is a secondary thermometer, i.e. it has to be calibrated. The material- and sensor-specific (for high accuracy) calibration curves are always only valid for ideal TC's. In real TC's - depending on operating conditions - the initial relationship between e.m.f. output and temperature (calibration curve) is lost after some time. In spite of these disadvantages the TC is used most frequently by far because it is

- a compact, robust sensor (mineral-insulated cable);
- simple and easy to handle;
- and emits a relatively large signal which can be easily transmitted.

B NOISE THERMOMETRY

Due to the basic disadvantages of thermocouples and other secondary thermometers, a new method which does not display the disadvantages of these thermometers has gained interest in the past few years: temperature measurement from thermal noise.

The random, statistical thermal agitation of the electrons in the conduction band of, for example, metal conductors is used for measurements. This electron movement, perceptible as a voltage fluctuation across a resistor, is a function of the absolute temperature and it is thus in principle possible to determine the temperature with the aid of suitable mean values (mean values because these are statistical processes).

This phenomenon is known above all in electrical engineering as the thermal noise of electric resistors. Fig. 8 shows the oscillogram of the amplified thermal noise of a simple metal film resistor (voltage fluctuations around zero with the linear average value of zero).

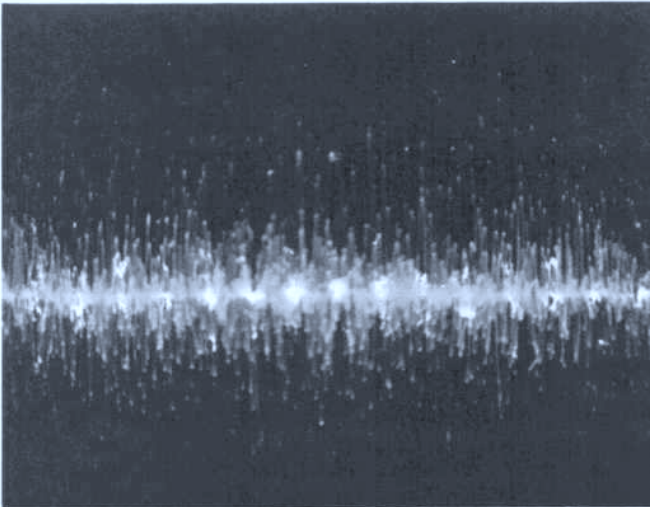


Fig. 8: Oscillogram of the amplified thermal noise of a resistor

The thermal noise of a conductor results from the interaction of a large number of individual processes occurring during the thermal motion of the charge carriers. If, for example, a shift in the freely movable electrons in a metal wire should occur by chance in such a manner that their common centre of charge is shifted at a particular instant towards one end of the wire, then this end displays a negative potential in comparison to the other end. On the whole, a stochastic voltage with a rapidly changing

sign results between the two ends of the wire due to the superimposition of a large number of such shifts.

1. NYQUIST'S THEOREM

Noise thermometry is quantitatively based on a relation established by Nyquist in 1928 from general thermodynamic considerations (second law of thermodynamics and the equipartition law) and experimentally confirmed in the same year by Johnson /18,19/. According to this theorem a voltage fluctuating statistically around zero occurs at the end of a passive network. The following is valid for the mean square of this voltage:

$$\overline{dV^2} = 4kT \operatorname{Re}(Z(f))df \quad (6)$$

(k = Boltzmann's constant; T = absolute temperature; $\operatorname{Re}(Z)$ = real part of impedance Z; f = frequency)

Equation (6) describes the noise of any passive unloaded network, quite irrespective of any special conduction mechanism. In ranges where quantum effects are of significance (i.e. hf is approximately equal to kT), formula (6) must be multiplied by a correction factor:

$$p(f) = \frac{hf}{kT} \left(\exp \frac{hf}{kT} - 1 \right)^{-1} \quad (7)$$

However, in all cases of practical interest this factor is equal to 1, i.e. at temperatures above 1K and frequencies below 10 MHz.

In practice, it is expedient to design the measuring sensor in such a way that the real part of the impedance is frequency-independent and only consists of an ohmic resistance R. The following is thus obtained by integration between a lower and an upper frequency limit

$$\overline{V^2} = 4kTR\Delta f \quad \Delta f = f_o - f_u \quad (8)$$

If one therefore measures the mean squared noise voltage $\overline{V^2}$ in a frequency interval Δf and the resistance R is also known then the absolute temperature of the resistance can thus be determined.

The principle of noise thermometry does not involve all those disadvantages found in conventional temperature measuring methods. As shown in Equation (8), all the environmental influences, such as reactor radiation or atmosphere, and similarly all influences from mechanical or thermal pretreatment, can only change the resistance R , similarly all the material properties and their variations only enter into R . This resistance can, however, be determined at any time by a measurement and thus all environmental influences etc. are precisely determined.

In contrast to the secondary thermometers which have to be calibrated, the noise thermometer is moreover a primary thermometer which directly indicates the absolute temperature.

2. MEASURING PROCEDURES TO DETERMINE THE NOISE TEMPERATURE

Fig. 9 depicts the basic diagram which can be used in principle to measure the noise voltage. The following is true of the mean squared noise voltage at the output of the integrator:

$$\overline{V^2} = 4kTR \int_0^{\infty} |A(f)|^2 df + \overline{V_e^2} \quad (9)$$

$A(f)$ is the frequency-dependent gain and V_e is the intrinsic noise of the amplifier.

Equation (9) gives some impression of the order of magnitude of the measured voltage to be expected if 300 K is substituted for the temperature, 100Ω for the resistance and 100 kHz for the frequency band. The following is then obtained with these values for the root of the mean squared noise voltage

$$\sqrt{V^2} \approx 4 \cdot 10^{-7} \text{ volt}$$

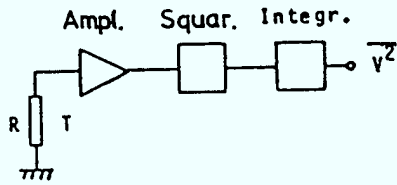


Fig. 9: Basic diagram of the noise thermometer

The major difficulty in electronically processing the noise voltages is therefore to be found in the low amplitudes of these voltages. For this reason it is useful to employ a comparative method as for example in Fig. 10, thus avoiding an absolute measurement of the noise voltages.

The measuring resistor R_M , with the unknown temperature to be measured T_M , and the reference resistor R_V , at the reference temperature T_V , are connected to the amplifier one after the other and then the resistance of R_V is adjusted in such a way that the mean squared noise voltages at the integrator output become equal: $\overline{V_M^2} = \overline{V_V^2}$

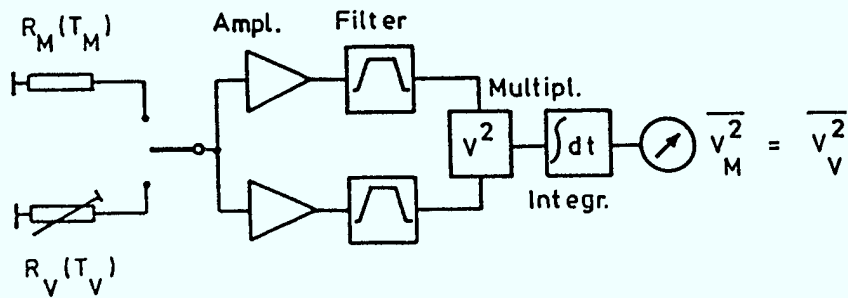


Fig. 10: Block diagram of the noise thermometer

The following simple equation is then valid for the unknown temperature

$$T_M = \frac{R_V}{R_M} \cdot T_V \quad (10)$$

The temperature to be measured, T_M is therefore equal to the quotient of two resistances times a reference temperature, T_V , specifying the scale. A fixed point can be selected as the reference temperature, e.g. the triple point of water (273.16 K, definition of the thermodynamic temperature scale),

but also any other known temperature, e.g. room temperature which particularly simplifies operational measurements.

Equation (10) shows that noise thermometry is an absolute temperature measuring method since only the scale (T_V) and a dimensionless scale factor (R_V/R_M) are used and no reference to any other physical quantity is needed. The arrangement of two parallel amplifiers with subsequent multiplication and integration results in the cross correlation of uncorrelated signals for the intrinsic noise of the amplifiers; amplifier noise is thus eliminated.

$$K_{12}(\tau=0) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T [V_s(t) + V_{e_1}(t)] \cdot [V_s(t) + V_{e_2}(t)] dt = \overline{V_s^2} \quad (11)$$

$K_{12}(\tau = 0)$ value of the cross-correlation function of the signals $(V_s + V_{e_1})$ and $(V_s + V_{e_2})$ at the input of the multiplier for the time shift $\tau = 0$ (/20/ p. 107)

V_s noise voltage signal of the measuring or reference resistor

V_{e_1}, V_{e_2} intrinsic noise of the amplifiers

Thus only the average products resulting from the noise voltages of the measuring resistor and the reference resistor, for which the circuit arrangement according to Fig. 10 means autocorrelation, appear at the output of the integrator. (Conclusions from finite measuring times T will be dealt with in section B7.)

A calibration of the amplifiers and an absolute measurement of the noise voltages are not required in the comparative method. The great advantage of the comparative method in comparison to an absolute measurement of the noise voltage is, however, to be primarily found in the insensitivity of this method to changes and disturbances occurring in the amplifier itself.

Noise temperature measurements have been carried out by measuring methods of this or a similar type at various locations, usually under laboratory conditions e.g. at low temperatures by Storm and Klempt who achieved accuracies of 0.3 mK in the range of 4 K /21,22/.

Measurements in the high temperature range were first carried out by Garrison and Lawson /23/.

Borkowski and Blalock used a method in which the noise voltage and the noise current are measured /24,25/. The multiplication of $V^2 = 4kTR\Delta f$ and $I^2 = \frac{4kT\Delta f}{R}$ then leads to the noise power $P = 4kT\Delta f$, which is independent of the value of the noise resistance. However, correction quantities must be considered in this method which, especially in the case of the noise current, are not easily determined. Great problems also arise with long transmission cables.

Since the absolute temperature is measured in noise thermometry this method is also used in metrology /26/. Crovini demonstrated that the International Practical Temperature Scale 68 deviates from the thermodynamic temperature scale at approx. 800°C by about 0.5 K /27/.

A historical review and survey of the literature is given in /28/.

3. MEASURING METHOD FOR DETERMINING NOISE TEMPERATURES UNDER PLANT CONDITIONS

A number of aspects become important in measuring noise temperatures under plant conditions which are insignificant or only of minor importance in laboratory measurements. This is true, for example, of the time-consuming calibration and compensation of the measuring apparatus, and of the (more or less effective) approximate consideration of the resistances of the cable wires between the sensor and amplifier etc. In particular, in the case of the often necessarily great distances between the sensor position and amplifier, the long connecting cables can influence the measuring signals.

For this reason, an electronic measuring system for noise

temperature measurements has been developed in the past few years at the KFA Jülich taking into consideration the special requirements of measurements under plant conditions. Fig. 11 shows a block diagram of this measuring apparatus.

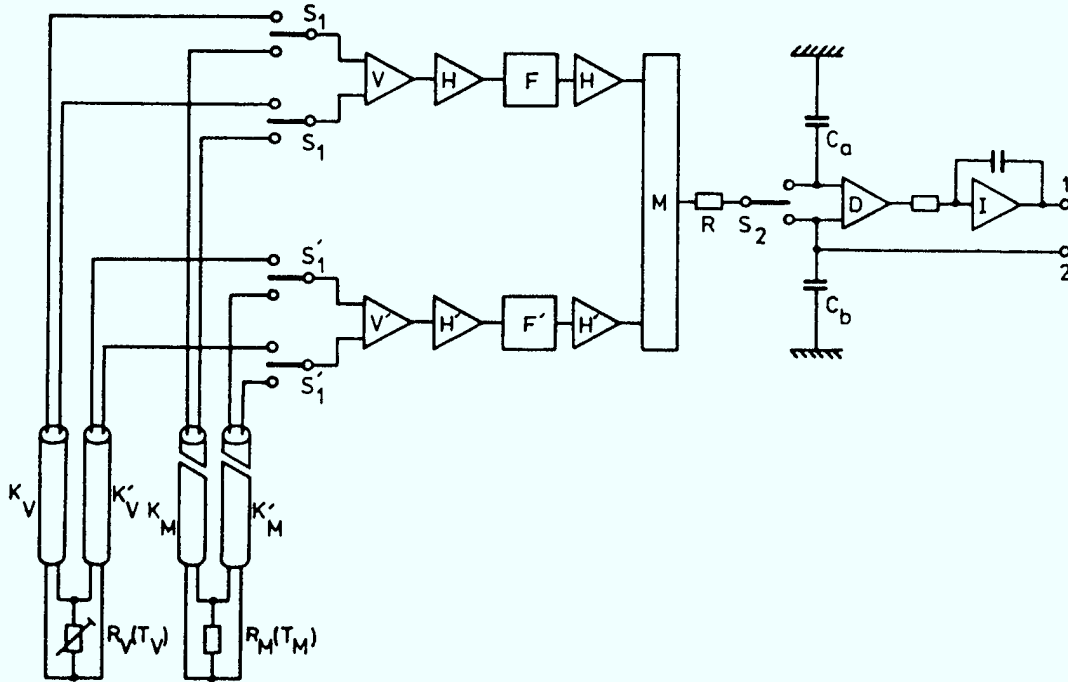


Fig. 11: Detailed block diagram of the noise thermometer

The coupling of the noise resistors can be seen in detail in this figure. The lead arrangement has two channels and reaches directly up to the measuring and reference resistor, and moreover both for the outgoing and also the return leads. It is thus possible to eliminate the noise voltages of all parasitic resistors, i.e. the noise voltages of the choppers and connection leads, in the same way as the inherent noise of the amplifiers by cross correlation.

The sequential scanning of the noise voltages of the measuring and reference resistor is performed by choppers S_1 and S_2 operating synchronously. For example, the noise signal of the measuring resistor reaches the capacitor C_a and the noise signal of the reference resistor the capacitor C_b . The "on" times of chopper 2 are selected in such a way that the switching spikes of chopper 1 are blocked.

During measuring operation, the resistor R_v is then altered in such a way that the signals on the capacitors C_a and C_b become equal. In order to increase the precision of this balance, the difference of these voltages is amplified and integrated. A voltage fluctuating statistically around zero which can best be registered on a recorder, is then obtained with completely balanced input circuits at output 1. Beyond comparing two noise voltages, the measuring method is moreover designed as a zero method. This feature also makes it easier to carry out measurements under plant conditions. However, it is also intended that the possibility of a direct measurement with stationary choppers should be included, in which case a mean direct voltage proportional to the absolute temperature results at output 2.

The combination of the various measures in the measuring process described

- comparative method (no absolute measurement of voltages)
- zero method (more convenient method for accurate measurements)
- two channels up to the noise resistors (correlation technique)
- differential inputs with high common mode rejection
- special chopper timing (blocking switching spikes)
- very sharp-cutting filters (eliminating of disturbed frequency ranges)
- special techniques to avoid or reject interferences

made it possible to construct a measuring device which can be used industrially under plant conditions.

Fig. 12 shows a photograph of the measuring device; it is a 19-inch device constructed on modular principles. The module technique was selected in order to be able to adapt the overall electronics to special measuring problems by replacing certain modules.

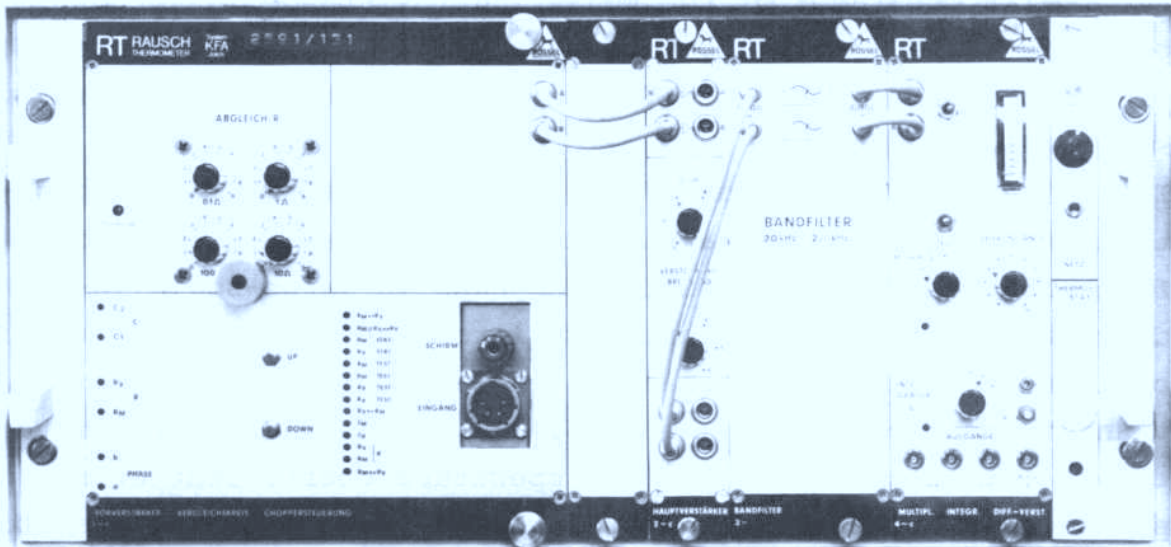


Fig. 12: Modular noise signal processor

4. NOISE THERMOMETER (NT) SENSOR

In the same way as a thermocouple and also a resistance thermometer, the NT sensor is a contact thermometer with all the resulting requirements such as good thermal coupling of the sensor etc.

In principle, a sensor consists of any electric resistor whose ends are connected to two wires insulated against each other; neither temperature coefficients nor any other variations in the value of the resistance are, in principle, of any significance. Pure metals and alloys are particularly suitable as resistor materials.

In contrast to resistance thermometers and thermocouples, the materials can therefore be largely freely selected. The particular choice can thus be adapted to the special measuring problem so that ambient conditions, material compatibilities, thermal expansion etc. are less important.

The value of the measuring resistance can be selected between approximately 1Ω and several $k\Omega$, the actual value being dependent on experimental conditions. Namely the higher the

temperatures, the smaller the resistances have to be.

Particular constancy of the measuring resistance is not of importance in the first instance when using NT sensors since this can be measured at any time (however, constancy during a measurement is necessary).

In the case of temperature measurements where the sensor position and measuring apparatus are at a considerable distance from each other, as is usually the case in large-scale industrial plants, the measuring resistor and the connection cable must be matched to each other in order to achieve good transmission behaviour (see Chap. B5). It is then appropriate to use materials with a small temperature coefficient of resistance in order to make a sufficiently good matching possible in a wide temperature range.

An alloy of 80 % Ni and 20 % Cr has proved to be particularly suitable. This alloy does not change its specific resistance by more than ± 2 to 3 % in the wide temperature range from 4 K to approximately 1600 K. Moreover, it can be employed in air up to the upper temperature limit due to its very stable surface oxide layer.

Metals or alloys with a high melting point are employed for measuring temperatures above 1500 K. Due to the relatively high temperature coefficient of resistance of these materials, the cable must be matched to the resistance value at the temperature to be measured.

Ceramic materials which have a small temperature coefficient of resistance at high temperatures can be advantageous here. A further advantage of ceramic materials is their generally higher durability when employed in adverse conditions.

5. SIGNAL TRANSMISSION THROUGH LONG CABLES

In the case of temperature measurements where the sensor position and the measuring device are at some distance from each other, as in nuclear reactors and industrial facilities in general, the connecting cable can influence the measurements if the noise signal in the selected frequency band is not transmitted undistorted. In the comparative method, the

white spectrum of the reference resistor transmitted practically undistorted through very short cables (approx. 20 cm) serves as a measure for the spectrum of the measuring resistor (usual range: 10 to 200 kHz).

Fig. 13 shows a typical cable arrangement for measurements under plant conditions.

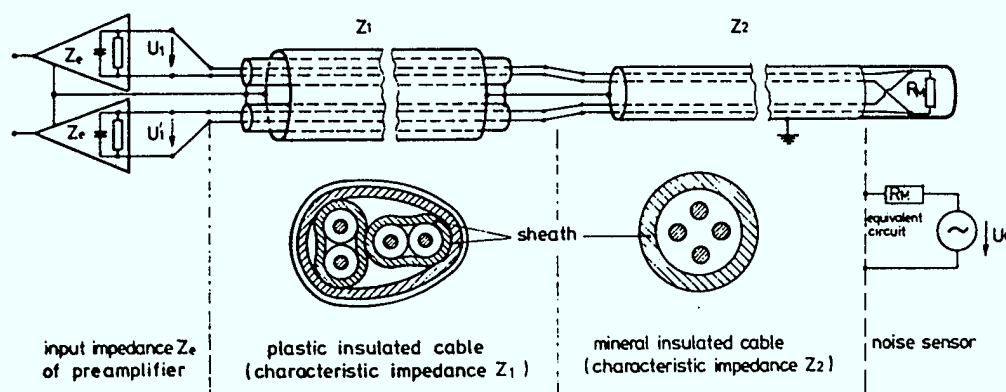


Fig. 13: Typical transmission cable arrangement in noise thermometry

The front line section with the measuring sensor consists at high temperatures of e.g. a four-wire mineral insulated cable. The line section at a lower temperature is designed with a two-wire symmetrical plastic-insulated cable.

By a special matching of the noise resistance R_M and the transmission cables, the transmission error in the frequency band used can be kept sufficiently small ($< 10^{-3}$) if necessary by reducing the upper band limit /30,31/. Thus for example measurements with accuracies of $1-2 \cdot 10^{-3}$ have been carried out with a cable length of 50 m (upper band limit 50 kHz). In general, the transmission cable should be kept as short as possible.

A further possibility of avoiding transmission errors is to install the preamplifier with the corresponding components as close to the measuring point as ambient conditions permit

(remote preamplifier). The measurements can then be undertaken from the control centre.

On the whole, the selection and matching of a sensor and a transmission cable for a certain measuring task is an optimization problem to be solved when the measuring setup is installed.

6. REJECTION OF INTERFERENCES

A very important point which requires particular attention with measurements in industrial plants is the avoidance or rejection of interferences.

Noise thermometer sensors generate extremely small signals which, moreover, have a large bandwidth. However, very long transmission cables are often required in industrial plants and strong electromagnetic interference fields which can produce undesirable interference signals in the transmission cables have to be reckoned with in such plants. They are superimposed on the sensor's signal and are correlated and usually in-phase so that they cannot be eliminated by the correlation technique.

Particular shielding techniques must therefore be applied in the presence of interference fields: the careful laying of cables in Cu and/or Fe pipes, the utilization of double-shielded cables. It has been shown in practice that the shields should be of as low impedance as possible. Ground loops must, of course, also be avoided or eradicated.

In many cases interference signals in the transmission cables cannot be avoided by shielding techniques alone. There are then in principle two possibilities of eliminating interference signals: blanking in the time domain or filtering in the frequency domain. Which of the two possibilities is to be applied depends on the type of interference signals.

The problem of interference rejection, even in very disturbed environments, could be satisfactorily solved by explicit

measures in all the examples described in Table 2 (Chap. C2). Nevertheless, the problem arises anew with each plant and must therefore be solved individually each time.

7. MEASUREMENT TIME AND ACCURACY OF NOISE TEMPERATURE MEASUREMENTS

A very important point for noise thermometry is the function of the measurement time with respect to the desired accuracy. Due to the stochastic nature of thermal noise, the accuracy of noise measurements is largely restricted by the statistics. The measured values of noise voltages, and thus the associated temperature values, therefore involve statistical errors. The following is true of the relative error of a measurement

$$\frac{\Delta T}{T} \sim \frac{1}{\sqrt{\Delta f \cdot \tau}} \quad (12)$$

Δf is the width of the frequency band used and τ the measurement time.

It follows from this equation that at a constant bandwidth the measurement time must, for example, be extended by a factor of 100 if the precision is to be increased by a factor of 10. Since the power spectrum of the noise in the frequency band used should be white and the bandwidth can therefore not be arbitrarily increased, the accuracy of noise temperature measurements is determined above all by the measurement time.

Equation (13) gives the precise formula for the relative statistical error of the measuring apparatus (Fig. 11) /20/:

$$\frac{\Delta T}{T} = \sqrt{\frac{2}{\Delta f \cdot \tau} \left(2 + \frac{B}{A} + \frac{C}{A} + \frac{BC}{A^2} \right)} \quad (13)$$

In spite of the elimination of amplifier noise by cross-correlation, the power spectra B and C of the amplifier chains' inherent noise appear once again[†]; they enlarge the relative

[†]B and C comprise all parasitic resistances, e.g. the resistances of the connecting cables, etc.

error. The power spectrum of the noise resistance itself (R_M or R_V) is designated A. The intrinsic noise of the measuring apparatus therefore plays a decisive role with respect to measurement time and one must endeavour to keep it as small as possible.

In order to give an example of the influence of the different variables, let the measurement time necessary for a precision of 1 % be given for the following combination of parameters: with a reference resistance at balance of $100\ \Omega$, and a bandwidth of 200 kHz and equivalent noise resistances of $100\ \Omega$ (in the mean-time equivalent noise resistances of $35\ \Omega$ have been realized), a measurement time of approximately 0.5 s results (or somewhat more than 0.1 s in the case of a direct measurement without choppers). The averaging time is increased to 50 sec (or 10 sec respectively) for 0.1 % precision.

If the parameters of the measuring arrangement are not so favourable (e.g. small measuring resistance, narrow frequency band), averaging times of 10 min and over are required for high precisions.

8. SENSORS AT HIGH TEMPERATURES

As in the case of TC's, mineral insulated sheathed cables are also used for NT's in the hot zone for measuring high temperatures. If the insulation resistances of mineral insulated cables are no longer sufficient then hard-sintered rigid ceramics (e.g. Al_2O_3 , BN, BeO) are used for the insulation.

As in the case of all contact thermometers, the relatively low electric resistance of the insulating materials also causes difficulties (electrical shunting error) for the NT at temperatures above about $1500^\circ C$ (depending on the length of the hot zone). In the case of the NT, the insulation resistance should be higher than the measuring resistance by a factor of at least 6 to 10 /30/. This means that in selecting the measuring resistance value this latter may only amount to a few Ohms.

Other problems, such as material compatibility and thermal expansion are less important for simple noise sensors than for thermocouples since there is greater freedom in selecting the materials and it is in principle possible to construct the sensor (apart from the insulation) from one material, i.e. the possibility exists of fabricating a practically single-material sensor (for example of graphite). Furthermore, the sensor material can be adapted to the respective ambient conditions.

C COMBINED THERMOCOUPLE-NOISE THERMOMETRY (TC-NT)

1. THE COMBINED SENSOR

Apart from its undisputed advantages, the noise thermometry described in Chapter B also displays certain disadvantages. For example, one disadvantage is that the electronic devices for processing the very small noise signals are sophisticated and expensive. A further disadvantage is that the measured signal is composed of stochastic signals and the temperature is proportional to the averaged value. A certain time is required for averaging, namely the more precise the measurements required, the longer it takes (/20/ Chap. B7). The NT is therefore particularly suitable for a discontinuous measuring method.

Significant advantages are therefore provided by a sensor developed at the KFA Jülich which combines a noise resistor with a thermocouple resulting in an extremely adaptable thermometer (Fig. 14, /29/).

It consists of a sheathed double thermocouple with two hot junctions. The noise resistor is positioned between the two hot junctions and insulated from the cladding.

This thermometer can be used both as a thermocouple as well as a noise thermometer. It thus combines the advantages of a TC with those of an NT.

It functions as follows. During most of the operating time, the e.m.f. of the thermometer is used for determining and recording temperature due to the simple and rapid way in which measurements can be carried out. There is, however, now the possibility of associating the correct absolute temperature to the e.m.f., which can change its value at constant temperature for a number of reasons, as often as required by means of the thermal noise of the resistor. It is therefore possible to calibrate or recalibrate the thermocouple in the thermometer at any time after installation, i.e. in situ.

The advantage of this calibration in situ is that all the parasitic thermovoltages resulting from temperature gradients

across inhomogeneous thermocouple wires are included in the calibration and thus measurement errors are avoided.

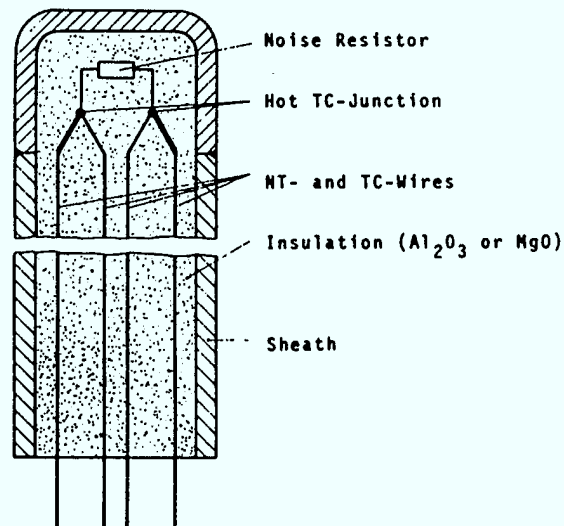


Fig. 14: Combined thermocouple-noise sensor

With this combined sensor it is now possible for the first time to detect and eliminate in practice the inhomogeneity errors. In many respects, the TC-NT thus has the properties of an ideal thermometer.

The 4 TC wires, which serve at the same time as signal wires for noise measurement offer the opportunity of eliminating the resistance of the wires by cross-correlation when measuring the noise temperature.

2. MEASUREMENTS WITH COMBINED THERMOCOUPLE-NOISE THERMOMETERS

Combined thermocouple-noise thermometers have been tested at a large number of sites and are now used under operational conditions in some industrial plants.

Table 2 gives a survey of sensor data and the conditions under which they were employed.

It gives an impression of the numerous possible variations for applying NT and combined TC-NT sensors.

Plant	Sensor				Transmission Cable		T	Position
	RT - TE (Materials)	R_M (cold) (Ω)	Mineral In- sulated Cable		Length (m)	Impedance (Ω)		
			ϕ (mm)	Length (m)				
FRJ2 Jülich	NiCr20-PtRh/Pt	25;60	2;3	4	20(+20 Test)	50	500-900	Core Region
KWO Obrigheim	NiCr20	25;46	2	9	15(+20 Test)	50;120	311	Core Region
AVR Jülich	NiCr20-NiCr/Ni	25	3;6	3	21;30	50	700-1000	Top-Reflector
GKN Neckar- westheim	NiCr30-NiCr/Ni	50	6	0,4	20;50; Remote Pre- ampl.	125	320	Primary Circuit
Oil/Gas- Power Plant	NiCr20-NiCr/Ni	35;50	6	0,4	5(+30 Test)	75;100	530	Steam Pipe
Coal-Gasifi- cation Plant	NiCr20-NiCr/Ni	17;50	6	2;6	3	35;100	850-950	Helium
EVA II Jülich	NiCr20-NiCr/Ni	17	6;4	3	10	35	1000	He-Heater
Ethylene Plant	NiCr20-NiCr/Ni	17	6	1	3	35	850-1150	Product Gas
Liquid Air Plant	NiCr20	120;300			6		-170	Liquid Air
Molten Glass	PtRh30-PtRh/Pt	7;10	1m Al ₂ O ₃ -Tube 15 mm ϕ		5(+20 Test)	35;50	1200-1350	Melt
Sintering Plant	WRe25-WRe3/WRe25	5	2m Al ₂ O ₃ -Tube 8,5 mm ϕ		2	150	1600	Furnace
HIP Plant	WRe25-WRe3/WRe25	2	0,5m in W-Tube of 7mm ϕ		3		2000	Furnace

Table 2: Sensor data and conditions of employment of NT and TC-NT sensors

In all cases accurate, undisturbed transmission of the measured signal was checked by selecting various frequency bands as well as controls in the time and frequency domain.

The measurement accuracy achieved was better than 0.5 % in all cases.

These measurements carried out under industrial conditions and in part in the presence of high electromagnetic interference fields indicate the applicability of noise thermometry as a measuring method under plant conditions.

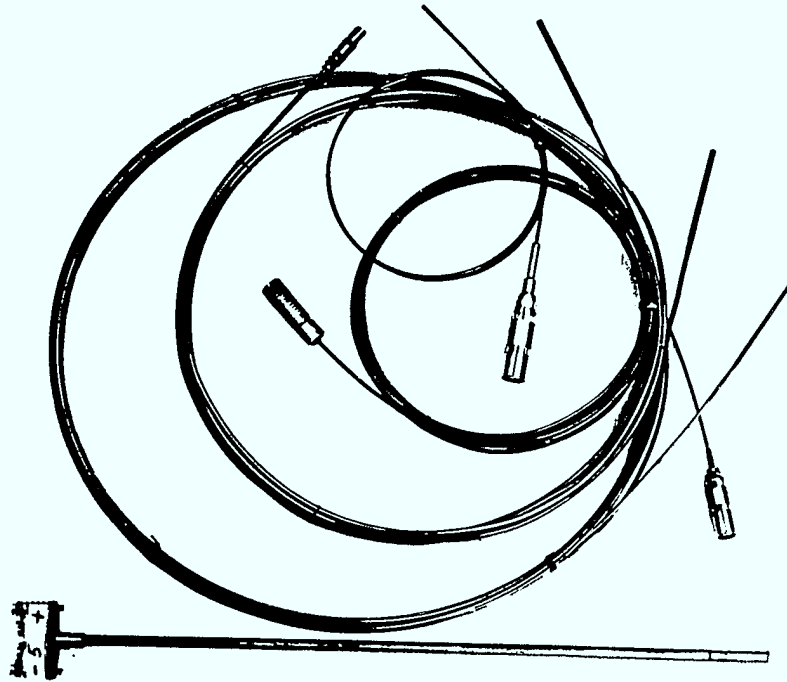


Fig. 15: Different types of combined TC-NT sensors

Fig. 15 shows combined sensors of different construction and dimensions. The sensors consist of four-wire mineral-insulated cables; they cannot be distinguished externally from conventional TC's.

D COMPARISON OF MEASURING METHODS

Noise thermometry is the first "thermodynamic" method not only used on a laboratory scale and for metrological purposes but which could also be employed under plant conditions.

Noise thermometry is based on thermodynamic principles and is independent of materials and material properties. It is therefore also independent of all changes in material properties such as occur in neutron fields in reactors, at high temperatures by the diffusion of impurities, phase transformations and recrystallization, and as result from mechanical and thermal treatment.

The noise thermometer is furthermore a primary thermometer which directly gives the absolute temperature.

In contrast to the noise thermometer, thermocouples make use of a specific material characteristic (thermopower) and its change with temperature. However, a large number of other effects are also known to influence the thermopower so that the temperature calibration curves - specific to the material and in part to the sensor - of these secondary thermometers are distorted after a relatively long operating time.

Due to its independence of ambient conditions and influences, the noise thermometer retains its initial accuracy even after very long operating times. It therefore has clear advantages over thermocouples, if relatively (i.e. depending on operating conditions) long operating times are required and the sensor is no longer accessible after installation.

Furthermore, the noise thermometer has the advantage of a greater choice of materials since it is not restricted to certain materials or pairings. It can therefore be more easily adapted to aggressive conditions in particular industrial plants.

The noise thermometer has the greater absolute accuracy. Depending on the effort and temperature range, 0.5 to 0.1 %

can be achieved for measurements under plant conditions. On the other hand, the thermocouple has the greater sensitivity.

The possible temperature range in which the noise thermometer can be applied is largely identical with that of thermocouples.

With respect to geometric dimensions (advantages for the TC in manufacturing sensor tips ≤ 2 mm) and handleability of the sensors, the noise thermometer and thermocouple are also comparable since both make use of e.g. mineral insulated cables for signal transmission in the hot zone. The noise thermometer is thus just as universally applicable as the thermocouple.

Due to the reading of the absolute temperature and the high accuracy achieved in the laboratory (0.1 % and better) noise thermometry can be used as a calibration method. It can be used to calibrate other temperature sensors (thermocouples, resistance thermometers) in a simple manner within a wide temperature range at any points.

The measurement time is determined in the case of precise noise temperature measurements by the averaging time for noise voltages and thus considerably exceeds the measurement time of thermocouples. This does not, however, in general play a significant role in the recalibration of combined thermocouple-noise thermometer sensors since recalibration is only carried out at fairly long intervals.

With respect to the economic aspect of choosing a method, the complex and in comparison very expensive electronic apparatus of the noise thermometer carries great weight. The noise thermometer will gain ground in competition with the thermocouple in cases where its superior characteristics are technologically urgently required or where economic profit can be expected (for example by higher yields from a process) by precise temperature measurement.

The application of combined sensors as depicted in Fig. 14

opens up many further application possibilities for noise thermometry in the industrial sector. Only one electronic device will then be required for recalibrating any number of sensors.

The combined thermometer unites the advantages of the thermocouple (simple measuring procedure, high sensitivity) with those of the noise thermometer (no decalibration, high absolute accuracy). In many respects it thus has the characteristics of an ideal thermometer.

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Abbrev. for : "Temperature, Its Measurement and Control in Science and Industry, Vol.4 (1972)": T4