JAERI-Review
96-003

NOISE THERMOMETER

March 1996

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日本原子力研究所
Japan Atomic Energy Research Institute

編集兼発行　日本原子力研究所
印　　刷　ニッセイエブロ株式会社

Noise Thermometer

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(Received January 29, 1996)

The noise thermometry (NT) is a temperature measuring method by which the absolute temperature measurement can be performed with a very high accuracy and without any influence of ambient environments and of the thermal history of its NT sensor (electric resistor). Hence it is quite suitable for application as a standard thermometry to the in-situ temperature calibration of incore thermocouples. The KFA Jülich had played a pioneering role in the development of NT and applied the results successfully to the AVR for testing its feasibility.

In this report, all about the NT including its principle, sensor elements and system configurations are presented together with the experiences in the AVR and the results of investigation to apply it to high temperature measurement. The NT can be adopted as a standard method for incore temperature measurement and in situ temperature calibration in the HTTR.

Keywords : Noise Thermometry, Jhonson Noise, Nyquists Theorem, Temperature Measurement, High-temperature, Absolute Temperature, Temperature Sensor, Electric Resistor, Thermocouples, Reactor Instrumentation

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The work was performed under contruct between Research Centre Jülich GmbH, KFA and Japan Atomic Energy Research Institute.

* Research Centre Jülich GmbH, KFA

JAERI-Review 96-003

熱雑音温度計

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（1996年１月29日受理）

熱雑音温度計は、センサの温度履歴や環境条件に左右されず、絶対温度を高精度で測定できる測定法である。温度標準としての役割はもとより、実際の炉内温度計として使われる熱電対などの現場校正用として最適な測定法である。西独ＫＦＡ研究所は開発の先駆者としてＡＶＲ炉などの原子力プラントにおいて、いち早く本測定法の試験をすすめていた。

本報告は、熱雑音温度計の原理をはじめ、センサ要素、システム構成など本測定法全般についての解説と、ＡＶＲ炉などのプラントでの実績を述べると共に、より高温測定におけるセンサ要素の検討結果をまとめたものである。今後、多目的高温ガス炉ＨＴＴＲの炉内温度計装及び現場温度校正用標準温度計として適用が展開できよう。

本報告書は、日本原子力研究所とドイツＫＦＡ研究所の協力研究により行った研究の成果である。

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PREFACE

In the Sensing Technology Laboratory (formerly the Reactor Instrumentation Laboratory), the development of Noise Thermometry (NT) has been carried out since early the 1980s to apply them to incore temperature measurement in the HTTR and to utilize as a standard thermometry for insitu temperature calibration. The NT is a temperature measuring method by which the absolute temperature measurement can be performed with a very high accuracy and without any influence of ambient environments and of the thermal history of its NT sensor (electric resistor). Hence it is quite suitable for application as a standard thermometry to the insitu temperature calibration of incore thermocouples.

Dr. Heinz Brixy of KFA Jülich had played a pioneering role in the development of NT and applied his results successfully to the AVR. In JAERI, the project of the VHTR (the multi-purpose very high temperature gas-cooled reactor) had started, where incore temperature measurements in a range of 1000 to 1200 ℃ were needed. This requirement could not meet with conventional thermocouples so that R & D was started to develop a new high temperature thermometry for the VHTR. Experiences in KFA Jülich and the needs in JAERI motivated the initiation of R & D collaboration, under the umbrella of KFA-JAERI cooperation for HTGR development, to develop the NT and thermocouples to meet the VHTR requirement.

In the period from May 1985 to March 1986, incore irradiation tests of KFA-developed NT sensors together with JAERI-developed thermocouples were carried out in the JMTR. In March 1990 and November 1991, calibration tests for JAERI-developed NT sensors were performed utilizing KFA's standard NT equipment. In 1993, Dr. Brixy stayed in the Sensing Technology Laboratory, JAERI, as a invited scientist, and discussed with JAERI staffs the adaptability of NT to incore temperature measurements and insitu temperature calibration in the HTTR.

Dr. Brixy has been a head of the reactor instrumentation development group in KFA and performed pioneering works in NT developments. His results have been applied not only to the AVR but also to LWRs, aerospace machines and temperature standards. He published many scientific papers, holds many patents and keeps fertile "know-hows" in temperature measurements. This report deals with all achievements performed by Dr. Brixy, as concerns high temperature measurements, and the results of discussion done between JAERI staffs and him. This contains almost all about the NT and hence would be very useful for engineers and scientists who intend to carry out high temperature measurements.

December 15, 1995
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序 文

センシング技術研究室（旧原子炉計測研究室）では、1980年代初期より多目的高温ガス炉HTTRの炉内温度計装及び現場温度校正用標準温度計として、熱雑音温度計の開発を進めてきた。熱雑音温度計は、センサの熱履歴や環境条件に左右されず絶対温度を高精度で測定できる計測法で、温度標準としての役割はもとより、実際の炉内温度測定に使われる熱電対の温度計測値の現場校正用として最適な測定法である。

当時西独KFA研究所では、熱雑音温度計開発の先駆者としてAVR等の原子力プラントにおいて、いち早く本測定法の試験を進めていた。一方、原研側の多目的高温ガス炉の炉心計測温度は1000℃～1200℃とAVRに比べ数段高く、無条件で適用できない状況にあった。そこで、原研とKFA研究所との協力研究のもとに、より高温での実用化を目指し本熱雑音温度計の開発を進めてきた。

1985年5月～1986年3月の間、原研大洗研究所JMTRにおいて西独KFA研究所が開発した熱雑音温度計の高温照射試験を実施した。また、1990年3月及び1991年11月には、原研側で開発した熱雑音温度計をKFA研究所に持ち込み、同研究所の所有する校正装置で比較校正試験を実施した。さらに、1993年10月には、KFA研究所のDr. H. Brixyを招聘し、HTTR炉内温度計装・現場温度校正用標準温度計としての適用可能性を、原研側の専門家と共に検討した。

Dr. H. Brixyは、KFA研究所における高温ガス炉開発プロジェクトの炉計装開発担当責任者として温度計装開発をリードしてきた専門家であり、特に、熱雑音温度計の研究者として世界のトップにあり、この分野で多くの研究論文や著書を持ち、特許・ノウハウも豊富に有している。本稿は、Dr. H. Brixyの豊富な研究実績をもとに、氏が来日中に原研側の研究担当者との間で行った技術指導や検討結果を纏めたものである。熱雑音温度計全般を包括する内容であり、その有用性と共に、今後の適用の展開を期待できる。

1995年12月15日
原子炉工学部
センシング技術研究室
荒　克之

1 INTRODUCTION

In measuring temperatures with contact thermometers, the problem may generally arise that the sensor is changed by influences of the environment, ie, the ambient effects change the measured quantity used in the sensor in an unpredictable and uncontrollable manner [70]. This is the case, for example, in high neutron fields, in highly aggressive atmospheres, and in any event at high temperatures (> 1000℃). 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 true of thermocouples and resistance thermometers [1 - 7].

Particularly at high temperatures, any sensor undergoes changes with time owing to the high temperature itself and therefore a measurement method is desirable which tolerates such changes, ie, which is not affected by such changes. A method capable of meeting these demands is noise thermometry. Here the random, statistical thermal agitation of the electrons in the conduction band of, for example, metal-conductors is used for measurement. 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 as the thermal noise of electrical resistors. Figure 1 shows the oscillogram of the amplified thermal noise of a simple metal film resistor (voltage fluctuations around zero with a linear average value of zero).

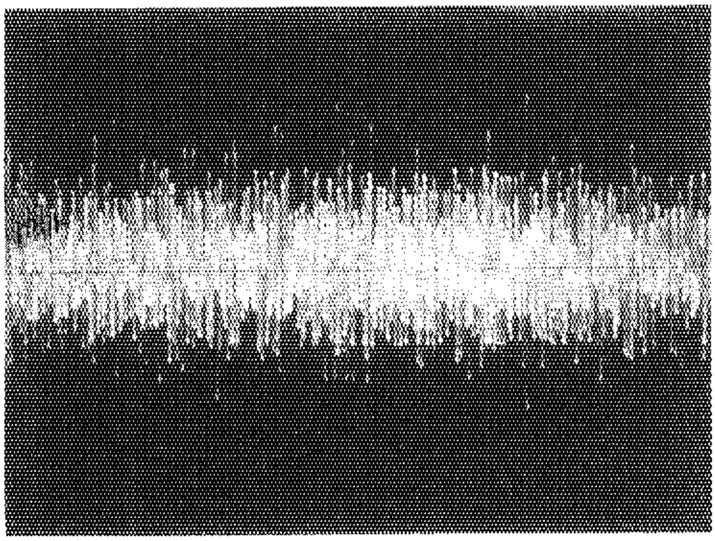


Figure 1 Oscillogram of (band - limited) thermal noise.

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.

2 FUNDAMENTALS OF NOISE THERMOMETRY

Special requirements are imposed on thermal noise sensors and measurements from measurement principles, signal transmission, etc. Therefore, the fundamentals of noise thermometry will be briefly reviewed .

2.1 Nyquist's Theorem

Noise thermometry is quantitatively based on a relationship established by Nyquist [8] in 1928 from general thermodynamic considerations without any reference to the atomistic structure of matter and which was experimentally confirmed in the same year by Johnson [9]. According to this theorem, a voltage fluctuating statistically around zero occurs at the ends of a passive electrical network (or sensor). For the mean square of this voltage, $d\overline{V^2}$, in a frequency interval df, the following equation holds :

$$d\overline{V^2} = 4k_B T \mathrm{Re}\left(Z\left(f\right)\right)df \tag{1}$$

or, as is also frequently written :

$$S = 4k_B T \mathrm{Re}\left(Z(f)\right) \tag{1a}$$

where k_B is the Boltzmann constant, T the absolute temperature, Re(Z) the real part of the complex impedance Z, f the frequency, and S the spectral power density or power spectrum of thermal noise

Equation (1) describes the noise of any passive unloaded sensor, irrespective of any special conduction mechanism. The thermal noise, often called Johnson noise, is independent of the internal structure of the sensing resistor (eg, physical state or chemical composition) and the nature of the charge carriers. Hence Equation (1) is valid for solid or liquid metals, carbon films, semiconductors, and also electrolytes. This provides great freedom in the choice of materials for the construction of sensing resistors.

In ranges where quantum effects are of significance (ie, $hf \sim k_B T, h$ being Planck's constant), Equation (1) must be multiplied by a correction factor :

$$p\left(f\right) = \frac{hf}{k_B T}\left(\exp\frac{hf}{k_B T} - 1\right)^{-1} \tag{2}$$

However, in all cases of practical interest this factor is equal to 1, ie, at temperatures above 1 mK and frequencies below 1 MHz.

The correction factor leads to a decrease in the power spectrum at high frequencies so that the total mean square noise remains finite. Another reason for the finite power of thermal noise is the unavoidable capacitances and inductances of the sensor which also cause a drop at high frequencies.

In practice it is useful to design the sensor in such a way that the real part of the impedance is independent of frequency and only consists of an ohmic resistance R. The following is thus obtained by integration between a lower (f_l) and an upper (f_u) frequency limit :

$$\overline{V^2} = 4k_B TR\Delta f \qquad \Delta f = f_u - f_l . \tag{3}$$

If one measures the mean square noise voltage, $\overline{V^2}$, of a resistor in a frequency interval Δf and resistance R is also measured, then the absolute temperature of the resistor is determined.

Equation (3) is the Nyquist equation in its simple form, which nevertheless holds for all practical applications of noise thermometry.

Equation (3) shows that all environmental influences (eg, from the atmosphere or nuclear radiation) and all influences from mechanical or thermal pretreatment can only change the resistance R. Also, all the material properties and their changes only enter into R. This resistance can, however, be determined at any time by a simple measurement and thus all environmental influences, etc., are precisely determined. The noise thermometer therefore shows no drift (as occurs, for example, with thermocouples or resistance thermometers), because all changes of the sensor are measured, ie, they are known and hence do not cause any measurement error.

These features distinguish noise thermometry from other temperature measuring methods, thus ensuring accuracy and long-term stability. Moreover, in contrast to most thermometers, which have to be calibrated, the noise thermometer is an absolute thermometer which directly indicates the thermodynamic temperature.

With such interesting features, the question arises of why noise thermometry is not widely used for metrological and industrial applications. The reason lies in the extremely small amplitudes of thermal noise voltages and the difficulty of electronically processing them. At the same time it must be ensured that external electromagnetic interferences are not superimposed on the useful signal noise. Both difficulties could only be overcome with the development of efficient electronic components in recent years.

Equation (3) gives an impression of the magnitude of the noise voltage to be expected if 300 K is chosen for the temperature, 100 Ω for the resistance and 100 kHz for the frequency band. With these values we obtain for the root of the mean square noise voltage

$$\sqrt{\overline{V^2}} \approx 4 \cdot 10^{-7} V. \tag{4}$$

2.2 Methods of Noise Thermometry

Figure 2 shows a basic diagram that can be used in principle to measure the noise voltage. The following equation holds for the mean square noise voltage at the output of the integrator :

$$\overline{V^2} = 4k_B TR \int_0^\infty \left|A(f)\right|^2 df + \overline{V_e^2}, \tag{5}$$

where A(f) is the frequency - dependent gain and V_e is the internal noise of the amplifier, corresponding to an equivalent noise resistance R_e.

According to Figure 2 and Equation (5), two measurements are necessary for the determination of the noise temperature (if one does not consider the amplifier gain A(f) and the internal noise $\overline{V_e^2}$, which can be determined separately) : the measurement of the noise voltage $\overline{V^2}$ with a high-input impedance voltage-sensitive preamplifier and the measurement of the noise resistance R with a d.c. or a.c. measuring instrument.

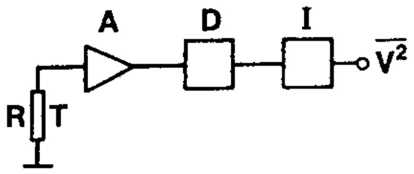


Figure 2 Basic diagram for measurement of the noise voltage (noise resistor R at temperature T; A, amplifier; D, square law detector; I, integrator; $\overline{V^2}$, mean square noise voltage).

A second method of determining the noise temperature results from a modified version of the usual Nyquist equation for the noise current of a resistor R :

$$\overline{I^2} = 4k_B T\Delta f / R. \tag{6}$$

From the measurement of the noise current, $\overline{I^2}$, with a low-input impedance current-sensitive preamplifier and the measurement of R, one also obtains the noise temperature.

A third method of determining the noise temperature results from the determination of the noise power of a resistor. Multiplication of Equations(3) and (6) gives the thermal noise power, P :

$$P = 4k_B T\Delta f. \tag{7}$$

Here the noise voltage $\overline{V^2}$, and the noise current, $\overline{I^2}$, have to be measured for the determination of the noise temperature. This method does not depend on the noise resistance R, which does not have to be known.

These three methods have often been realized with different signal-processing techniques and, mostly, highly sophisticated electronic circuits. A historical review up to 1982 for both metrological and industrial applications was given by Blalock and Shepard [10].

A fourth basic method of noise thermometry, which can be used only at very low temperatures and employs quantum devices such as Josephson junctions, is briefly described in Section 6.3 .

In the following, a measurement process is descried which is most suitable for both industrial and metrological applications. This measurement process is based on the comparison of the noise voltages of two resistors and according to the first method, noise voltages and resistances or rather the ratios of the two are measured. This measurement technique was first reported by Garrison and Lawson [11] and used later in a great variety of arrangements [12-31]. For the elimination of the unwanted amplifier noise a correlation technique is often applied, feeding the noise of the sensing resistor into two amplifiers connected in parallel [32-39]. The combination of the comparison with the correlation technique [6,18,19,21,22,30] leads to a measurement process with good conditions for the whole field of application of noise thermometry.

As shown in Figure 3, the sensing resistor R_S at the unknown temperature T_S and the reference resistor R_R at the known reference temperature T_S are connected in turn to the inputs of the amplifiers. For the temperature to be measured one obtains form Equation (5)

$$T_S = \frac{\overline{V_S^2}}{\overline{V_R^2}} \cdot \frac{R_R}{R_S} \cdot T_R \tag{8}$$

where $\overline{V_S^2}$ and $\overline{V_R^2}$ are the square noise voltage of the sensing and reference resistors. $\overline{V_e^2}$ is eliminated by cross correlation (see below). If R_R is adjusted until

$$\overline{V_S^2} = \overline{V_R^2} \tag{9}$$

then the unknown temperature becomes

$$T_S = \frac{R_R}{R_S} \cdot T_R . \tag{10}$$

The temperature to be measured, T_S, is therefore equal to the ratio of two resistances times a reference temperature, T_R, specifying the scale. A fixed point can be chosen as the reference temperature, eg, the triple point of water (273.16 K), but also any other known temperature, eg, room temperature, which particularly simplifies process temperature measurements.

Equation (10) shows that the noise thermometer is an absolute thermometer since only the defining point on the temperature scale (T_R) and a dimensionless scale factor (R_R / R_S) are used and no reference to any other physical quantity is needed.

The arrangement of two parallel amplifiers with subsequent multiplication and integration

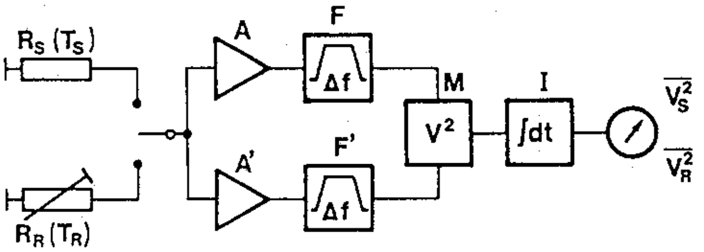


Figure 3 Block diagram of the comparison and correlation noise thermometer (Rs, sensing resistor ; T_S, temperature of the sensing resistor, temperature to be measured; R_R, reference resistor; T_R, temperature of the reference resistor, reference temperature; A, A', amplifiers; F, F', filters; M, multiplier; I, integrator, $\overline{V_S^2}$, mean square noise voltage of the sensing resistor; $\overline{V_R^2}$,mean square noise voltage of the reference resistor).

results in the cross correlation of uncorrelated signals for the internal noise of the amplifiers ; amplifier noise is thus eliminated.

$$K_{12}(\tau = 0) = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left[V_S(t) + V_{e_1}(t)\right] \cdot \left[V_S(t) + V_{e_2}(t)\right] dt = \overline{V_S^2} \tag{11}$$

K_{12} (τ =0) , value of the cross-correlation function of the signals (V_S+V_{e1}) and (V_S+V_{e2}) at the input of the multiplier for the time shift τ =0 ([19] p. 107)
V_S, noise voltage signal of the measuring or reference resistor
V_{e1}, V_{e2} , intrinsic noise of the amplifiers

Consequently, only the averaged products resulting from the noise voltages of the sensing resistor and the reference resistor, for which the circuit according to Figure 3 means autocorrelation, appear at the output of the integrator. (Conclusions from finite measurement time τ will be dealt with in Section 2.4.) It is not necessary to know the gain or bandwidth of the amplifiers and the linearity or stability of gain does not exhibit problems either if the comparison technique is used.

Similarly to the described method of measuring the noise voltage and resistance, the method of the measuring the noise power has also found wide application [40-48]. The power method has advantages if the real part of the impedance of the sensor is frequency dependent [48], but this method also has some disadvantages. Different approaches to noise thermometry signal processing have been reported [49, 50].

2.3 Measurement Process for Determining Noise Temperatures

A number of aspects become important in practice when measuring noise temperatures under both industrial and laboratory conditions which are directly related to the sensor construction. These are the signal wires in the sensor and the electrical potential of the sensor.

A noise temperature measurement process which takes this into account is shown in Figure 4 [6, 19, 30].

The coupling of the noise resistors can be seen in detail. The lead arrangement has two channels and reaches directly to the sensing and reference resistors, and moreover for both the outgoing and also the return leads. It is thus possible to eliminate the noise voltages of all parasitic resistors, ie, the noise voltages of the switches and connection leads, in the same way as the internal noise of the amplifiers by cross correlation.

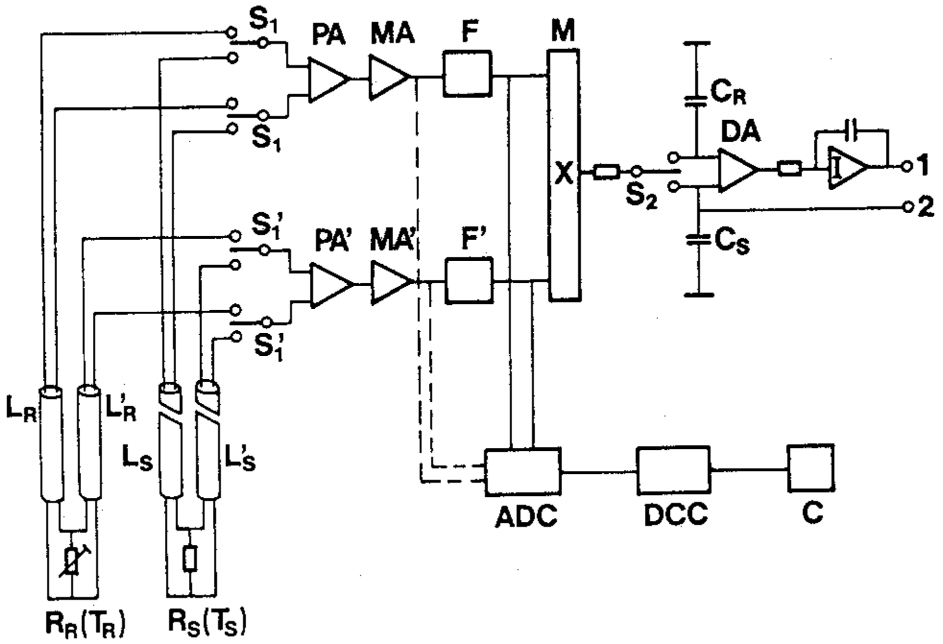


Figure 4 Detailed block diagram of a practical noise thermometer system ($R_S(T_S)$, sensing resistor at temperature T_S; $R_R(T_R)$, reference resistor at temperature T_S; L_S, L_S', leads (cables) to the sensing resistor R_S; L_R, L_R' leads (cables) to the reference resistor R_R; S_1, S_1', S_2, switches; PA, PA', preamplifiers; MA, MA', main amplifiers; F, F', filters; M, multiplier; C_S, C_R, storage capacitors for the noise signals of R_S and R_R, respectively; DA, differential amplifier; I, integrator; ADC, analog to digital converter ; DCC, digital cross correlator; C, computer and control unit ; AD conversion, behind F, F'(or MA, MA' with digital filtering)).

[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_S and the noise signal of the reference resistor the capacitor C_R . 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_R is then altered in such a way that the signals on the capacitors C_S and C_R become equal. In order to increase the precision of this balance, the difference of these voltage 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 two-channel arrangement of the connection cables between R_S or R_R and the electronic device means that the preamplifiers must be designed as differential amplifiers. Differential amplifiers make a high common mode rejection of external interference signals possible.

The amplifier noise is inevitably twice as strong as in the case of a single ended input amplifier. Admittedly this increases the measuring time which has to be tolerated.

In a large number of applications the sheath of the sensor is inevitably connected to ground at a remote point ; this ground potential is in many cases different from the ground potential of the device. The preamplifiers are therefore supplied from a separate power pack with a shielded transformer. The signal cable's sheath (sensor sheath) can now be connected to the independent potential of the preamplifiers. The signal connection from the preamplifiers to the successive stages takes place by means of either transformer or differential amplifiers. This type of signal and ground connection in the input section has proved effective in practice. Behind the filters, F, F' (or main amplifiers MA, MA') the analog signals are digitized and then digitally processed. For historical reasons, analog signal processing behind the filters is also shown and described above [in brackets].

The combination of the various measures in the measuring process described

- comparative method (no absolute measurement of voltages)
- nearly zero method (more convenient method for accurate measurements)
- two channels up to the noise resistors (correlation technique)
- deferential 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.

Figure 5 shows a functional block diagram. The electronic system for processing the signals is designed for measurements with combined sensors, ie., processing both the noise and thermocouple signals (TC-NT signal processing system). The electronic system (based on the comparison and correlation method) is divided into the preamplifier and the main device. The preamplifier with its components is installed as close to the sensor as ambient conditions permit (remote preamplifier). The signals at the output of the preamplifier can then be transmitted over long distances (up to several hundred meters), usually to the control room.

The whole automated measuring procedure of the TC-NT system is controlled by a computer in the main device.

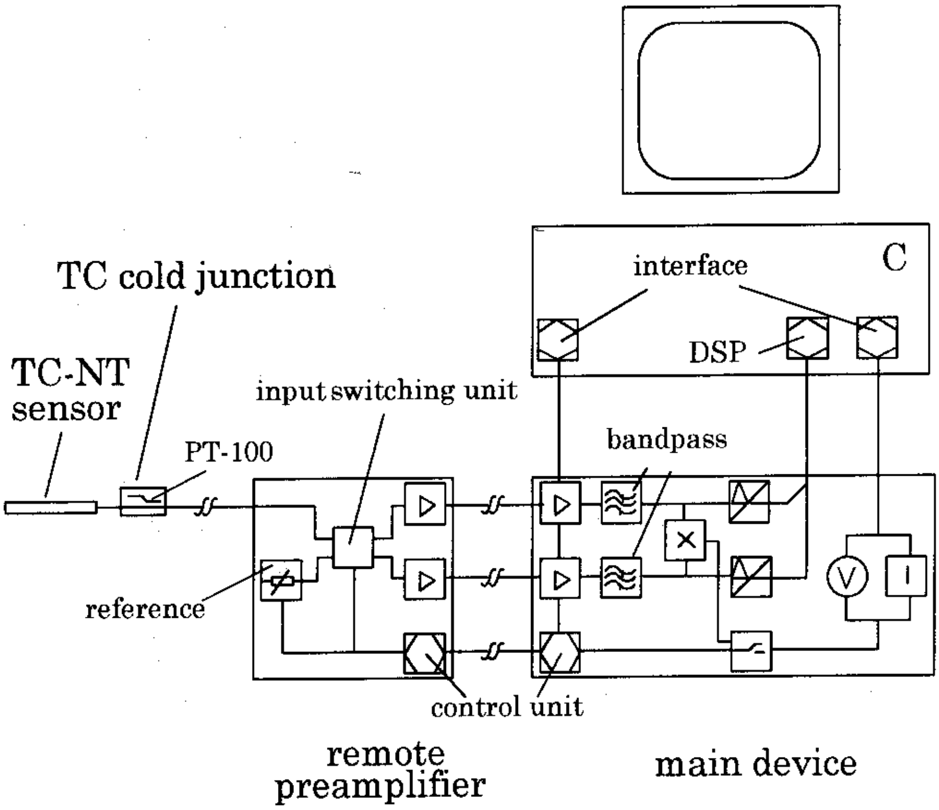


Figure 5 Functional block diagram of the KFA noise thermometer (DSP : digital signal processor; C: computer).

2.4 Measurement Time and Statistical Accuracy

An important point for noise thermometry, which among other things has significance for selecting the value of the noise resistance, the design of the sensor and measurement set-up, is the function of the measurement time with respect to the desired accuracy. Owing to the stochastic nature of thermal noise, the precision 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 expression holds for the relative error of a measurement [51] :

$$\frac{\Delta T}{T} \sim \frac{1}{\sqrt{\Delta f \cdot \tau}} \qquad \text{(Rice formula)} \tag{12}$$

where 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 (see Section 2.5) and the bandwidth therefore cannot be arbitrarily increased, the accuracy of noise temperature measurements is also determined by the measurement time.

Equation (13) gives the precise equation for the relative statistical error for the comparison noise thermometer system in Figure 4 in a symmetrical form [19] at a confidence level of 0.68 (1 σ) :

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

In spite of the elimination of amplifier noise by cross correlation, the power spectra B and C of the amplifier chains' internal noise appear once again; they increase the relative error. The power spectrum of the noise resistance itself (R_S or R_R which are equal at balance) is designated by A. The internal noise of the preamplifiers therefore plays a decisive role with respect to measurement time and one must endeavor to keep it small as possible. This is particularly true if small sensing resistances have to be used (eg, when measuring high temperatures, see Section 4.4).

An equivalent noise resistance R_e, of 24 Ω for a differential preamplifier has been reported [34]. It should be possible to obtain values of R_e as low as ca. 10 Ω by connecting several FETs (field-effect transistors) in parallel and cooling them to an optimum temperature.

If the resistances of the connection cables between the sensing resistor and electronic device become relevant in comparison with the equivalent noise resistance of the amplifiers then they must be taken into account accordingly in B and C with respect to the averaging time for V_s^2.

With a direct measurement of the noise voltage with stationary switches, ie, not using the comparison method, a measurement time is needed for the same precision which is shorter by a factor of 4:

$$\frac{\Delta T}{T} = \sqrt{\frac{1}{2\cdot\Delta f\cdot\tau}\left(2+\frac{B}{A}+\frac{C}{A}+\frac{BC}{A^2}\right)}\,. \tag{14}$$

In this case, however, the electronic device has to be calibrated, which can be carried out with the aid of the reference resistor. The time saved in the direct measurement is needed for the previous calibration. Equations (13) and (14) hold in all cases, although shorter times are often reported in the literature.

In order to give an example of the influence of the different variables, let the measurement time necessary for an statistical uncertainty (1 σ) of 1% be given for the following combination of parameters : with a reference resistance at balance of 100 Ω, and a bandwidth of 200 kHz and equivalent noise reisistances of 100 Ω (in the meantime equivalent noise resistances of 35 Ω 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% statistical uncertainty (1 σ).

If the parameters of the measuring arrangement are not so favourable (eg, small measuring resistance, narrow frequency band), averaging times of 10 min and over are required for 0.1% statistical uncertainty. For high precision measurements of the temperature of the Zn fixed point (419.527 ℃) with a statistical uncertainty $\leqq 5\times10^{-5}$ measurement times of $\geqq$ 4h became necessary in practice (parameters : Rs=32 Ω,Re=60 Ω, Δf=180 kHz) [68] (see also Section 6.2.1).

By way of comparison with the correlation method, consider the relative error for only one amplifier chain with square-law detector [19] . For this circuit one obtains for the relative statistical error :

$$\frac{\Delta T}{T} = 2\,\frac{A+B}{A}\cdot\frac{1}{\sqrt{\Delta f\cdot\tau}} = \frac{2F}{\sqrt{\Delta f\cdot\tau}} \tag{15}$$

where $\frac{A+B}{A}$ is the amplifier's noise figure F.

A comparison of the two formulae (13) and (15) with respect to the measuring time results in :

$$\frac{\tau_k}{\tau_a} = \frac{1}{2}\left(1+\frac{1}{F^2}\right) \tag{16}$$

with B = C (τ_k from (13) ; τ_a from (15)).

Equation (16) shows that the method with two amplifier chains, as opposed to one, can halve the required measuring time, and especially if the amplifier's noise figure is large. Since the noise figure enters as the square, the measuring time is almost halved even at F = 2.

2.5 Signal Transmission

In the case of conventional temperature-measuring sensors, such as thermocouples and resistance thermometers, the measured signals are DC voltages, in connection with which the transmission behavior of the lines (cables) is principally governed by the ratio of series resistance to insulation resistance. The noise thermometer's measured signal in practical applications consists of frequencies between about 5 and 300 kHz. The frequency-dependent transmission characteristics of the signal cables must therefore be taken into consideration in noise thermometry.

In the comparison method, the white noise spectrum of the reference resistor is transmitted to the preamplifier input via such short lines that it appears undistorted (in the above-mentioned frequency range). Since this undistorted reference spectrum serves as a measure of the sensor noise spectrum, the white noise spectrum of the sensor must also be transmitted to the preamplifier without distortion in the frequency band used (this also holds for methods other than the comparison method).

Figure 6 shows a typical cable arrangement. The front line section with the sensing resistor consists at high temperatures of, eg, a four-wire mineral-insulated cable. The line section at a lower temperature is designed with a two-wire symmetrical plastic-insulated cable. The sensing resistor is represented in the equivalent circuit diagram as the series circuit of a noiseless resistance R_S with noise voltage source V_S.

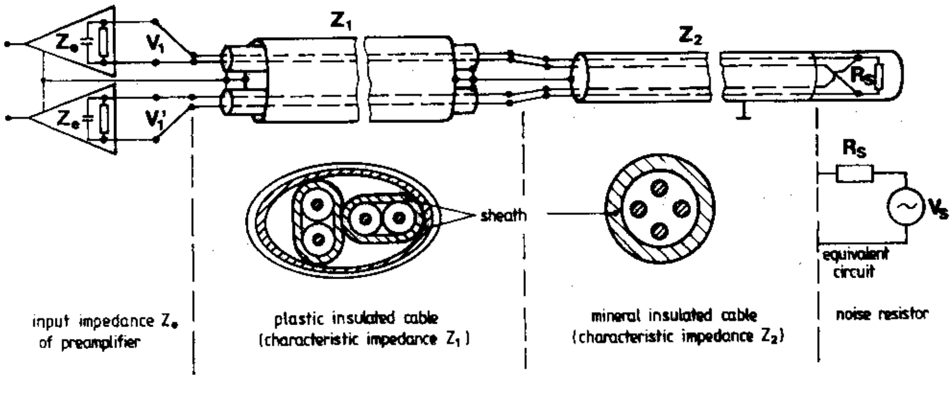


Figure 6 Typical transmission cable arrangement in noise thermometry.

In laboratory measurements with usually short cable lengths, the effects on transmission are less significant, but in industrial measurement, where the sensor position and the electronic measuring device are, in general, at some distance from each other, the noise spectrum of the sensing resistor can be considerably affected.

By a special matching of the noise resistance (R_S) 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 [30,52]. Thus for example, measurements with accuracies of $1 \cdot 10^{-3} - 2 \cdot 10^{-3}$ have been carried out with a cable length of 50 m (upper band limit 50 kHz ; averaging time ca.10 min) [53].

Another possibility for avoiding transmission errors is to install the preamplifier with the corresponding components as close to the sensor as ambient the conditions permit (remote preamplifier). The signals can then be transmitted over long distances, usually to the control room. A further possibility is to calculate or measure the overall system frequency response and to compensate for the distortions [45,48]. In general, the cables should be as short as possible.

A more detailed description of signal transmission in noise thermometry is given in Annex 1 (see also [52]).

2.6 Rejection of Interferences

The most severe problem in noise thermometry which requires particular attention with measurements in both industrial plants and the laboratory is the detection and avoidance or rejection of external interferences. These interferences can be of electromagnetic or mechanical (eg, vibrational) origin. Vibrations can cause changes in the distances of the lead wires and internal components of the sensor (microphonic noise) and they can cause Barkhausen noise in ferromagnetic lead wires and resistors (see Section 4.3), but electromagnetic interferences (EMI) are usually much more important.

Noise thermometer sensors generate extremely small signals which, moreover, have a large bandwidth. Therefore, EMI induced in the sensor and/or the transmission line due to electric, magnetic, or electromagnetic fields, and electric currents flowing in the cable shields, can cause significant errors. The interference signals are superimposed on the sensor's signal in both channels and are correlated and usually in-phase so that they cannot be eliminated by the correlation technique. A relative measurement error then results for the noise temperature, which is given by the ratio of interference power to useful noise power in the frequency band used.

Careful attention must be paid to the choice of cables (dual, shielded, twisted-pair, arrangement of the four lead wires, see Figure 6) and their installation (remote from power or control lines and units), and particular shielding techniques must be applied (preferably double shielding, lying of the cables in Cu and/or Fe or stainless-steel tubes). 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 eliminated.

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 and filtering in the frequency domain. They are complementary to each other and they are sufficient. Which of the possibilities (or both) is to be applied depends on the type of interference signals [30,54].

Phase-controlled thyristor plants, as well as high power rectifier plants in general, have proved to be particularly responsible for interferences in practice. Since interference spikes with repetition frequencies synchronous to the mains are involved in these cases, the signal paths in the electronic measuring apparatus can be briefly interrupted if an interference spike of this type is expected. A two-channel blanking unit, which provides blanking pulses synchronous to the mains with repetition frequencies of 50 Hz, 100 Hz, 150 Hz and 300 Hz, has proved in practice to be appropriate. The blanking pulses can be varied both in their duration as well as in their phase position with respect to a reference signal.

When picking up continuous interference signals which are in limited frequency ranges, an undisturbed frequency band is chosen for the measurement, i. e. the interferences are filtered. The bandpass filters with sharp slopes already mentioned, with which disturbed ranges can be selectively suppressed, have here proved to be of use.

Interference signals with mains frequency and multiples of this, which can be significantly larger than the useful signal, are sometimes coupled (see discussion of plant EVA Ⅱ in Section 6.1) and can possibly overload the main amplifier. A comb filter has been successfully employed to suppress them.

A high common-mode rejection of the differential preamplifiers also has a very favorable effect with respect to parasitic interferences because it eliminates part of the interferences that appear as common-mode signals on the transmission lines [30,38]. Another possibility of removing the EMI noise power is to measure it quantitatively and subtract it from the useful noise power [46,48] . However, as the EMI effect is in general not readily amenable to correction, the best strategy is to eliminate it by the measures described above.

The problem of interference rejection is different for each measuring task and must therefore be solved individually each time.

The problem of interference rejection, even in very disturbed environments, could be satisfactorily solved by explicit measures with all the applications described in Section 6.

2.7 Requirements for the Sensor

Owing to the extremely small amplitude and the wide band width of the noise signals, the transmissions and processing are more complex and elaborate here than in other temperature measuring methods. For the same reasons, the sensor has strong connections to transmission and processing and vice versa. Therefore, requirements are made on the sensor from the characteristics described in the previous sections.

The cross correlation in signal processing to eliminate the parasitic noise of the transmission lines (R_L) requires four lead wires to the sensing resistor. The correlation technique is particularly important at high temperatures because, owing to decreasing insulation resistances of the sensors, small values for the sensing resistances (R_S) have to be chosen and, therefore, the ratio of the useful signal noise to the parasitic cable noise becomes disadvantageous. In addition, the lead resistances are at undefinable temperatures so that their noise cannot easily be eliminated by other measures. The low R_S values at high temperatures, further, make low equivalent noise resistances of the preamplifiers and low R_L values desirable for realizing short measurement times or, conversely, the R_S values selected must not be too small because of measurement time (see Equation (13)). The necessity for an undistorted signal transmission (Section 2.5) requires special matching of the R_S value and cable [52] or, if this is not possible, a reduction of the upper band limit. However, such a band limitation increases the measurement time.

If low temperatures are to be measured, high R_S values are necessary. Then the cables must be short, ie, the preamplifier has to be installed near to the sensor.

To realize an optimum EMI rejection it is advantageous to employ sensors with the noise resistor R_S insulated from ground. The efficiency of the shielding here is usually better the higher the insulation resistance can be kept.

At very high temperatures the sensor resistance commonly becomes unstable even for short times. Then it is favorable to employ the direct measurement method (with previous calibration of the electronic device) and not the comparison method. This reduces the needed measurement time by a factor of 4. Additionally the band width should be kept as wide as possible.

Overall, the selection and matching of a sensor for a certain measuring task are an optimization problem to be solved when the measuring set-up is being designed and installed.

3 COMBINED THERMOMETRY

Apart from its undisputed advantages, described in Section 2.1, noise thermometry 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 necessary for averaging, namely the more precise the measurements required, the longer it takes (Section 2.4).

3.1 The Combined Thermocouple-Noise Thermometer Sensor (TC-NT Sensors)

Significant advantages are therefore provided by a sensor which combines a noise resistor with two thermocouples, resulting in an extremely adaptable thermometer [55]. It consists, as shown in Figure 7, of a sheathed double thermocouple with two hot junctions. The noise resistor is positioned between the two junctions and insulated from the cladding.

This thermometer can be used both as a thermocouple (TC) and as a noise thermometer (NT). It therefore combines the advantages of both instrument types. It functions as follows. During most of the operating time, the emf of the TC is used for determining and recording the temperature due to the simple and rapid way in which measurements can be carried out. There is now, however, the possibility of associating the correct absolute temperature with the emf, 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 sensor at any time after installation, ie, in situ. The advantage of this in situ calibration 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. With this combined sensor it is now possible to detect and eliminate quantitatively in practice the inhomogeneity errors of thermocouples, because this can only be done by in situ calibration. In many respects, therefore, the TC-NT has unique properties.

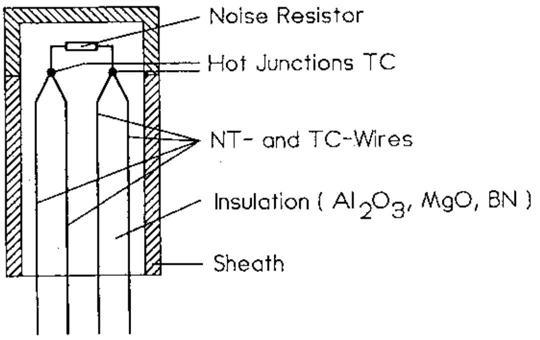


Figure 7 Combined thermocouple-noise thermometer sensor

The four 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. This is of particular impedance here because of the sometimes considerable resistance of the usual TC wires (eg, NiCr/Ni wires). Moreover, when using combined sensors only one electronic device for processing the noise voltages is necessary. With this device it is possible to recalibrate from time to time any number of sensors.

It is in principle also possible to carry out a simultaneous measurement with a combined thermocouple-noise temperature sensor, since thermocouple provides a direct voltage whereas the noise resistor provides a fluctuating voltage which can be fed out by means of a capacitor.

3.2 Combined Resistance-Noise Thermometry

According to the Nyquist equation (Equation (1)), any electrical resistor can be used as a noise thermometer. This also holds, of course, for the resistor of resistance thermometers (RT), which can therefore serve as noise thermometers. In the same manner as described above for the combined TC-NT sensor, noise thermometry can be employed for in situ calibration and recalibration of RTs. However a problem may arise with the usual RT sensors, because the d. c. resistance is not generally the same as the noise resistance (ie, the real part of the sensor impedance Re(Z(f)) within the pass band of the measurement). The difference between the two depends on the resistor construction. A reduction of the upper band limit can be a solution in some cases. The application of the noise power method for processing the noise signals generally solves the problem, because in the power method the resistance does not need to be known [40].

In practice, restrictions are imposed on the application of RTs as noise thermometers owing to the difficulty of achieving a satisfactory match with the transmission cable.

If the four lead wires of a resistance thermometer are made of TC material, all three methods (TC, RT and NT) can be employed with one sensor.

4 SENSORS FOR NOISE THERMOMETRY AND COMBINED THERMOCOUPLE - NOISE THERMOMETRY

4.1 General Aspects

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

In principle, a sensor consists of any electrical resistor whose ends are connected to two or four 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 measurement problem so that ambient conditions, material compatibilities, thermal expansion, etc, are less important.

4.2 Value of Noise Resistance and Temperature Range

The value of the noise resistance can be selected between approximately 1 Ω and several kilohms, the actual value being depending on the experimental conditions, namely the higher the temperatures the smaller the resistance have to be. The reason for this is the decreasing insulation resistance of the sensor with increasing temperature and the necessity for avoiding insulation errors, similarly to the case with thermocouples and resistance thermometers (see also Section 4.4).

At very low temperatures (ca.4K), metal film resistors are preferably used with values up to 20 k Ω [34, 35]. A high sensor resistance ensures that the noise power (which is proportional to RT) retains an appropriate value. Short connecting cables have to be used here for an undistorted signal transmission which can be performed easily in laboratory measurements.

In the range from room temperature up to about 1200℃, mostly resistance values between 100 and 10 Ω are chosen. Such values are adequate for a good match with the transmission cable. At very high temperature (above 1500℃), only a few ohms are feasible for the sensor owing to insulation problems, as mentioned above. It may be of historical interest that Johnson in 1928 employed resistance values up to a few megaohms [9].

4.3 Materials for NT and TC-NT Sensors

Great constancy of the sensor resistance is not of importance in the first instance when using NT sensors, since the resistance can be measured at any time (however, constancy during averaging is necessary). In temperature measurements where the sensor position and electronic device are at a considerable distance from each other, as is usually the case in large-scale industrial plants, the sensor resistance and the connection cable must be matched with each other in order to achieve good transmission behavior (see Section 2.5). It is then appropriate to use materials with a low temperature coefficient of resistance in order to make a sufficiently good match possible over 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 3% in the wide temperature range from 4 K to ca. 1600K. Moreover, it can be employed in air up to the upper temperature limit owing to its very stable surface oxide layer. Most of metal film resistors used at low temperature also have NiCr resistance layers.

Metals or alloys with a high melting point are employed for temperatures above 1500 K (W, Re Mo, Rh, Pt, etc.). Owing to the relatively high temperature coefficient of resistance of these materials, the cable must be matched with the resistance value at the temperature to be measured.

Compatible materials are in general used for combined sensors, eg, an NiCr alloy is chosen as resistor material together with NiCr TCs, Pt, Rh or a PtRh alloy with PtRh TCs, and W, Re or a WRe alloy with WRe TCs. For insulation the same materials are employed as for TCs and RTs at high temperatures, eg, Al_2O_3, MgO, BeO, HfO_2, BN, etc.

In a similar way the materials for sheaths and protection tubes are chosen to be compatible with the respective environment and, if possible, with the TC and NT materials.

Compatibility with environmental conditions means for noise sensors not only compatibility with the existing atmosphere and the surrounding materials, but also electromagnetic compatibility. Electromagnetic compatibility in this context means that the materials chosen for the sensor resistor and the lead wires are insensitive to external alternating magnetic fields. In ferromagnetic materials, such alternating magnetic fields, if they are high enough, can generate Barkhausen noise; the power spectrum of this noise does decrease with rising frequency, but may be relevant in the whole frequency range of noise thermometry if it is strong enough (pink noise) [70,71].

High alternating magnetic fields arise especially in plants which are operated with high alternating currents from mains (eg, large high-temperature furnace plants). If the sensor resistor is made of a ferromagnetic material, then magnetic interferences with 100-Hz repetition frequency occur in the sensor noise at temperature below the Curie point (Figure 8).

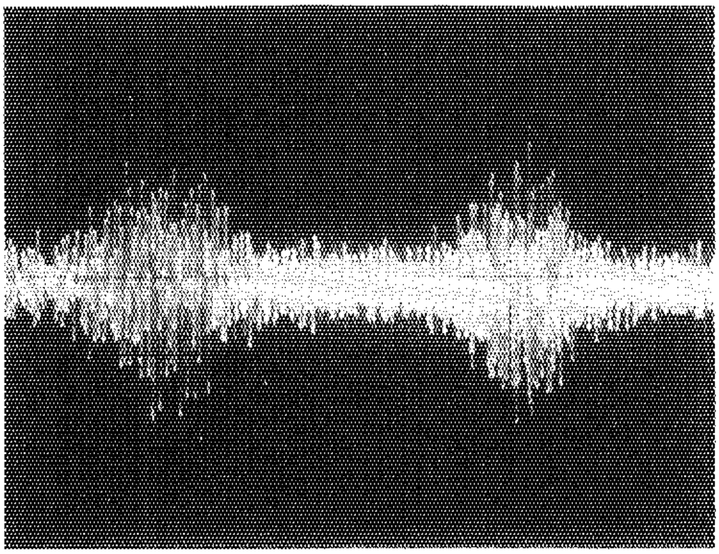


Figure 8 Oscillogram of the noise of a combined sensor with NiCr/Ni thermocouples superimposed by Barkhausen noise from the Ni wires (magnetic antinodes induced by alternating magnetic fields of a.c. current from 50 Hz mains ; time window 20ms).

The same is true of ferromagnetic wire materials in cables because the external alternating magnetic field causes to a large extent correlated interference noise, so that the correlation technique has no effect. As the cables are also positioned in cold regions, ie, below the Curie point, it is not possible in such cases to employ, for example, combined NiCr TC-NT sensors. Even materials which have such a low content of Fe or Ni as to be usually regarded as non-magnetic may show Barkhausen noise in strong alternating magnetic fields.

Ferromagnetic materials are often applied for effective shielding of external alternating magnetic fields ; in extremely strong fields, however, the Barkhausen noise generated in the shield can couple into the lead wires; in such cases, non-magnetic shielding have to be applied.

Apart from alternating magnetic fields, Barkhausen noise can also be generated by mechanical shocks or vibrations. If the sensor or the cable is subject to such stresses, ferromagnetic materials must also be avoided here.

4.4 Sensors at High Temperatures

As with thermocouples, mineral-insulated sheathed cables are also used for noise thermometers in the hot zone when measuring high temperatures. If the insulation resistances of mineral-insulated cables are no longer sufficient, then hard-sintered, rigid ceramics (eg, Al_2O_3, BN, HfO_2, BeO) are used for the insulation. As in the case of all contact thermometers, the relatively low electrical resistance of the insulating materials also causes difficulties (electrical shunting error) for the NT at temperatures above about 1500 ℃

(depending on the length of the hot zone). In the case of the NT, the insulation resistance should be higher than the sensing resistance by a factor of at least 6 (see Annex 2). This means that in selecting the sensing resistance value this latter may only amount to a few ohms, or at very high temperatures, ie, 2000 ℃ and above, also to values below 1 ohm.

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, ie, the possibility exists of fabricating a practically single-material sensor (eg, of graphite). Further, the sensor material can be adapted to the actual ambient conditions.

As mentioned in Section 2.7, the resistance value often varies at high temperatures within relatively short times owing both to the high temperature itself (eg, recrystallization, evaporation) and to influences from the environment (eg, diffusion, chemical reaction). Then the direct measurement method (Section 2.4, Equation(14)) must be employed owing to the shorter averaging times and, possibly, a higher statistical error must be tolerated. The application of both measures then allows an on-line, quasi-continuous readout of the temperature to be made.

5 DESCRIPTION OF ACTUAL NT AND TC-NT SENSORS

The general possibility of using any electrical resistor for noise thermometry has been restricted in some respects in the previous sections, for various reasons.

From a multitude of feasible forms some construction types have been developed with favorable characteristics and proved successful in practice Thus, noise resistors with two or four lead wires are employed, but four lead wires together with the correlation technique have advantages. The noise resistor can be grounded or insulated from ground ; owing to the better possibilities of interference rejection, however, mainly insulated resistors are used. Further, the resistors should be designed for small inductances and capacitances to show white noise in the frequency band of measurement. It is often desirable to keep the dimensions of the sensor small. With noise sensors geometrical dimensions can be realized in such cases that are comparable to those of corresponding thermocouples or resistance thermometer. However, minimum diameters of thermocouples below ca. 1.5 mm are difficult to realize with noise sensors.

5.1 Construction Types of Noise Resistors

For reasons of historical documentation, in Figure 9 a noise resistor and sensor is shown which had already been used in 1949 for noise temperature measurements up to 1050℃. The sensing resistor is made from 2.5 - μm platinum Wollaston wire, welded to heavy platinum leads 1.3 mm in diameter [11].

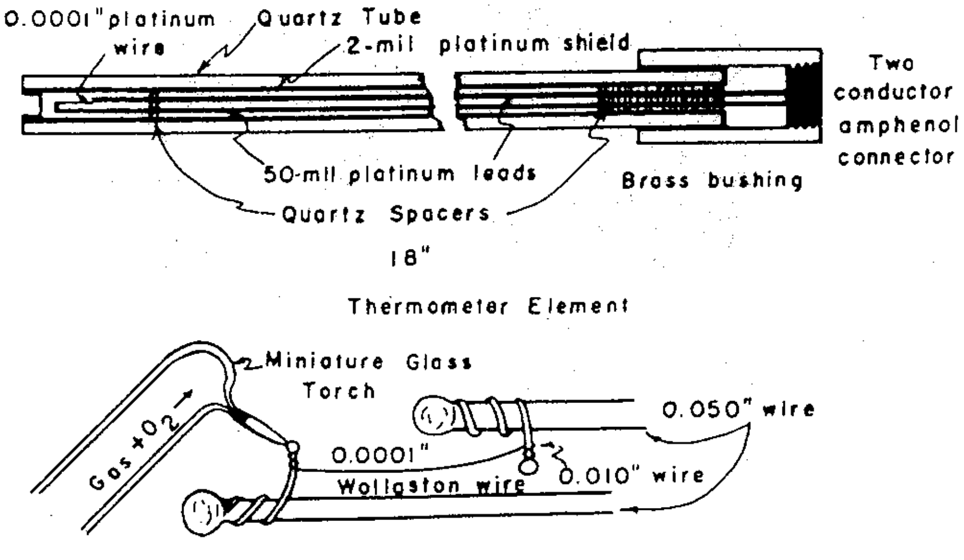


Figure 9 "Historical " noise resistor and sensor for high temperature (from [11]).

A more durable construction is exhibited by the noise resistor in Figure 10. A metal wire is threaded in a meandering way through a multi-hole ceramic body, thus forming a stable sensing element with both low inductance and low capacitance.

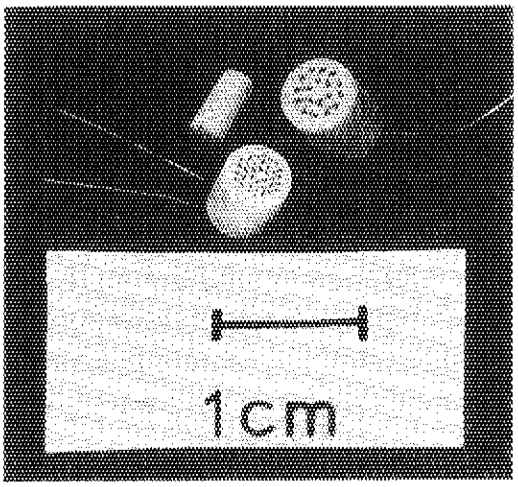


Figure 10 Threaded noise resistors. Resistor, eg, metal wire (NiCr 8020, diameter 0.15 mm) in a 36-hole ceramic (Al_2O_3, diameter 4.6 mm), resistance value 17 Ω.

Similar construction types of noise resistors for very high temperatures are shown in Figure 11.

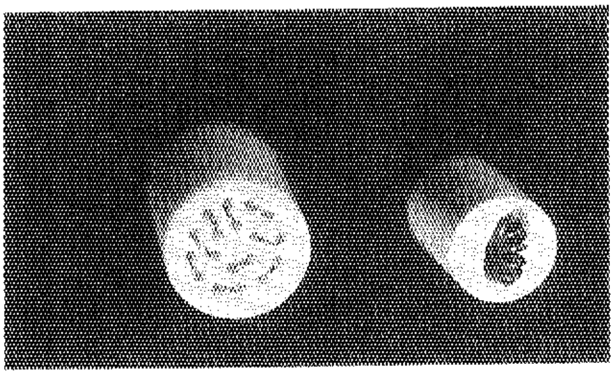


Figure 11 Construction types of noise resistors ; (left) threaded noise resistor : metal wire (Pt Rh 30, diameter 0.15mm) in a 18-hole ceramic (Al_2O_3, diameter 5 mm), cold value 2.5 ohm ; (right) coiled noise resistor : metal wire (WRe26, diameter 0.2 mm) in a 2-hole ceramic (BN, diameter 4 mm), cold value 0.5 ohm, coil pulled out for clarity.

Another construction of a noise sensor for high temperatures is shown in Figure 12 [44]. It is a combined sensor in a two-wire configuration with an Re coil as a noise resistor and one WRe thermocouple. To eliminate microphonic noise caused by vibration of the internal components, fine insulation powder (HfO_2) is compacted in all voids around the sensing coil and lead wires. Another method for reducing microphonic noise is to swage the sensor down and in this way compact the insulators, which are crushable.

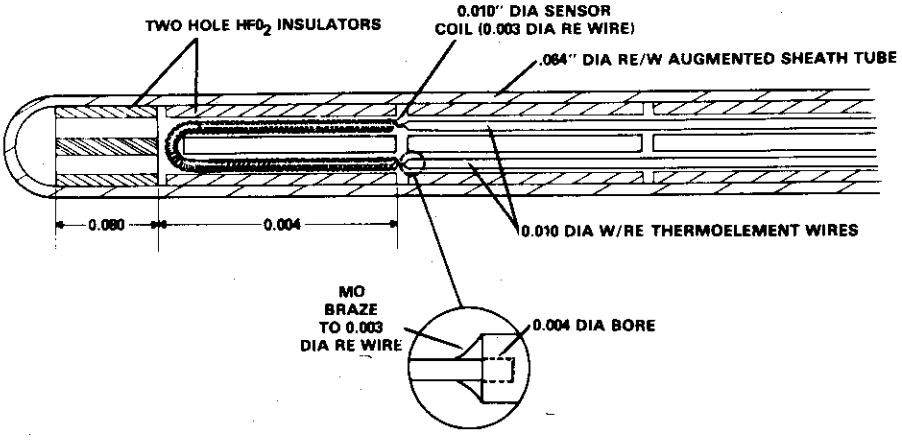


Figure 12 Illustration of 2200℃ JNPT (Johnson noise power thermometer) design using 0.010-in o.d. sensor coil (from [44]).

In general, all the different construction designs of resistance thermometers and metal film resistors can also be used for noise resistors, but care must be taken to keep the inductances and capacitances low to ensure white noise in the frequency pass band.

5.2 Sensors for Different Temperature Ranges

Commercial film resistors can be employed from very low temperatures (a few kelvin) up to several hundred kelvin. Resistors with a non-inductive design, due to a special serpentine pattern, are available from different manufacturers.

Resistors of the construction type in Figures 10, 11 and 12 are suitable for the whole temperature range if the materials are selected appropriately. For high temperatures ceramic insulators (Section 4.3) are used and high-melting metals and their alloys serve as resistor wires, in addition to carbon fibers and filaments. The electrical shield necessary in most cases can be made from a refractory metal or graphite. Most important in this connection is the compatibility of the materials. The dimensions of the insulators of the construction type shown in Figure 10 reach down to about 1 mm diameter (eg, six-hole tube of Al_2O_3). Concerning the wire diameter, filaments down to ca. 0.01 mm are used in practice. However, for high temperatures the wire diameters should not be chosen to be less than 0.1 mm for long-term durability reasons.

For temperatures up to about 1200℃ mineral-insulated sheathed cables (MI cables) are employed, similar to those used for thermocouples. Figure 13 shows combined sensors of different construction and dimensions. The sensors consist of four-wire MI cables with the noise resistor between the two hot junctions of the TCs in the tip (see also Figure 7). Such sensors are as robust as ordinary TCs ; they cannot be distinguished externally from TCs.

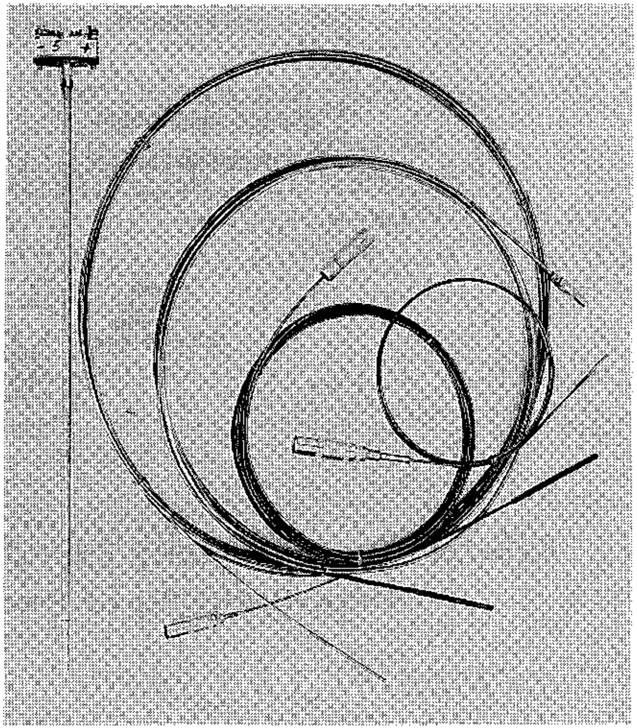


Figure 13 Different types of combined TC-NT sensors with mineral-insulated sheathed cables.

5.3 Sensors for Metrological Applications

The Nyquist law is based on very fundamental considerations and gives a simple relationship for the thermodynamic temperature ; it therefore provides in principle a firm basis for establishing a temperature scale. Noise thermometry has been used for temperature scale metrology up to now in the temperature range 1-1360 K [23-25,27-29,31,34-39,56]. At low temperatures metal film resistors with, for example, a serpentine pattern are employed as sensors, whereas at higher temperatures Pt resistance thermometers with non-inductive performance and sensor constructions as in Figures 10 and 11, with wires of Pt, PtRh, W, Re and NiCr alloys are employed.

Important aspects for sensor construction are a negligible skin effect, small capacitances and inductances, or a balance of these two, to ensure white noise in the frequency band of measurement [19, 56]. Special attention has to be paid to electromagnetic interferences which must be reduced well below 10^{-4} ; for this purpose an appropriate sensor construction (effective shielding, dual twisted pair arrangement of the lead wires) can be helpful. At high temperatures leakage my become a problem [30]. The ratio of insulation to sensor resistance must be sufficiently high, up to the upper temperature limit. Therefore, small sensor resistance (R_S) have to be chosen. With the comparison method, linearity errors of the electronic device can be avoided by inserting into the lines of the reference resistor (R_R) resistance values that generate the same parasitic noise as is generated by the sensor line, so that at balance the useful and parasitic noise of the R_R circuit has the same magnitude as that of the R_S circuit. As the correlation technique works effectively with short cables, correlation errors are negligible [52]. Using sensors with the described characteristics, uncertainties down to 10^{-4} have been realized at high temperatures (> 500 ℃) and to some 10^{-5} at low temperatures.

For the future, the noise thermometer appears very promising even beyond 1000℃ because it has the exceptional advantage over other methods that any changes in the sensor are of no significance.

5.4 Development Trends for Noise Sensors

As described in Section 5.2, metals and alloys with high melting points (Pt, Rh, W, Re, etc.) have been applied in the production of noise resistors for temperature above 1200℃. However, the often low durability of the noise resistors manufactured from thin wires or films is disadvantageous in practice. Moreover, a protective atmosphere or vacuum is often needed for their application.

5.4.1 Ceramics as Materials of Noise Resistors

The Nyquist equation in its general form (Equation (l)) is valid for any material, ie, including ceramics. In contrast to metallic resistors, ceramic noise resistors can be manufactured much more robustly, and they can also be employed in chemically harsh (eg, oxidizing) atmospheres.

When the comparison method is used to measure the noise temperature, however, some requirements have to be fulfilled by ceramic resistors. The noise power spectrum must be white in the frequency range used (up to ca. 200 kHz), and the resistance should be independent of an applied small voltage (eg, measuring voltage, thermovoltage). A low temperature coefficient of resistance in the temperature range used (>1000℃) is also desirable. Other requirements are a high melting point, high thermal and chemical stability, a low vapor pressure in the temperature range applied, and a small resistivity so that specimens can be manufactured that are easy to handle [57-60].

Most ceramics are insulators, but many can be manipulated by doping to make them show electronic conductivity, the order of magnitude of which can be adjusted with the nature and amount of the dopant. In this way, usable specimens with resistance values between about 20 and 1 Ω in the temperature range 1000-2000℃ can be manufactured.

A general difficulty in using ceramic materials for noise resistors which cannot be overcome easily, is the contact problem of the connecting lines (signal lines) to the noise resistor [72].

5.4.2 Compact Construction of Noise Resistors

As mentioned above, a robust and compact type of construction is possible for ceramic resistors. Disk-shaped or cylindrical specimens can be fabricated. The manufacturing process is simple and the samples can be produced cheaply.

In a similar manner compact, cylindrical resistors can be fabricated from, eg, NiCr powders which are mixed with an insulation powder raising the resistivity. Robust noise resistors can also be fabricated by sintering, eg, coiled wires (as in Figure 12) in suitable insulation powders. Moreover it seems possible to enclose wire noise resistors with insulation powders using a plasma spray process.

5.5 Graphite Noise Sensors

In measuring the thermodynamic temperature in the high-temperature range with the aid of noise thermometry combined WRe sensor are preferred today. These sensors have a noise resistor, eg of WRe26, and two thermocouples, eg, of WRe5/WRe26, in the sensor tip with the noise resistor positioned between the two hot junctions of the thermocouples and insulated from the sheath (Figure 7).

5.5.1 Problems with Usual Materials at High Temperatures and Possible Solutions

The thermocouple drift problem is solved in the combined WRe sensors by the fact that the thermocouples can be recalibrated in situ at any time via the noise resistor and thus always display the true temperature. Their limited durability is a disadvantage for combined sensors, particularly if temperature cycles are performed. The WRe wires become brittle due to the poor compatibility of the sensor material with, eg, carbon materials of the environment (chemical reactions of WRe with C) and by recrystallization; due to the different thermal expansion coefficients of the two WRe wires, these wires then break in the case of temperature changes or very slight mechanical stress (eg,shocks, vibrations). The mechanical service life of the combined WRe sensors is therefore just as limited as that of simple WRe thermocouples (which, however, give incorrect reading for a considerable period before fracture).

One of the advantages of noise thermometry is that it is material-independent since the Nyquist formula is valid for any electric resistors. In contrast to resistance thermometers and thermocouples, the materials can therefore largely be freely selected. The particular choice may then be adapted to the special measuring problem so that environmental conditions, material compatibilities and thermal expansion are less important. In the case of simple noise thermometers it is furthermore also possible to manufacture the sensor (apart from the insulation) from a single material; ie, it is possible to fabricate a practically single-material sensor. In a carbon environment, graphite is obviously the optimum material [73].

5.5.2 Noise Thermometer Sensors of Carbon Cord

With a sensor of this type, the noise resistor itself and also the four signal lines consist, for example, of braided graphite cord (Figure 14), and the insulation of BN beads and the sheath of graphite or carbon-fibre-reinforced carbon tube (CFRC tube) [74]. On the one hand this provides a high compatibility in plants with a carbon environment and on the other hand solves the problems of thermal expansion for the noise resistor and the signal lines by the material composition (single-material system) and the structure (braided design). Furthermore the complete sensor (graphite cord, CFRC tube) is insensitive to mechanical shocks and vibrations even after long-term operation at elevated temperature. A sensor with good durability and a long service life is thus available for application in the high-temperature range.

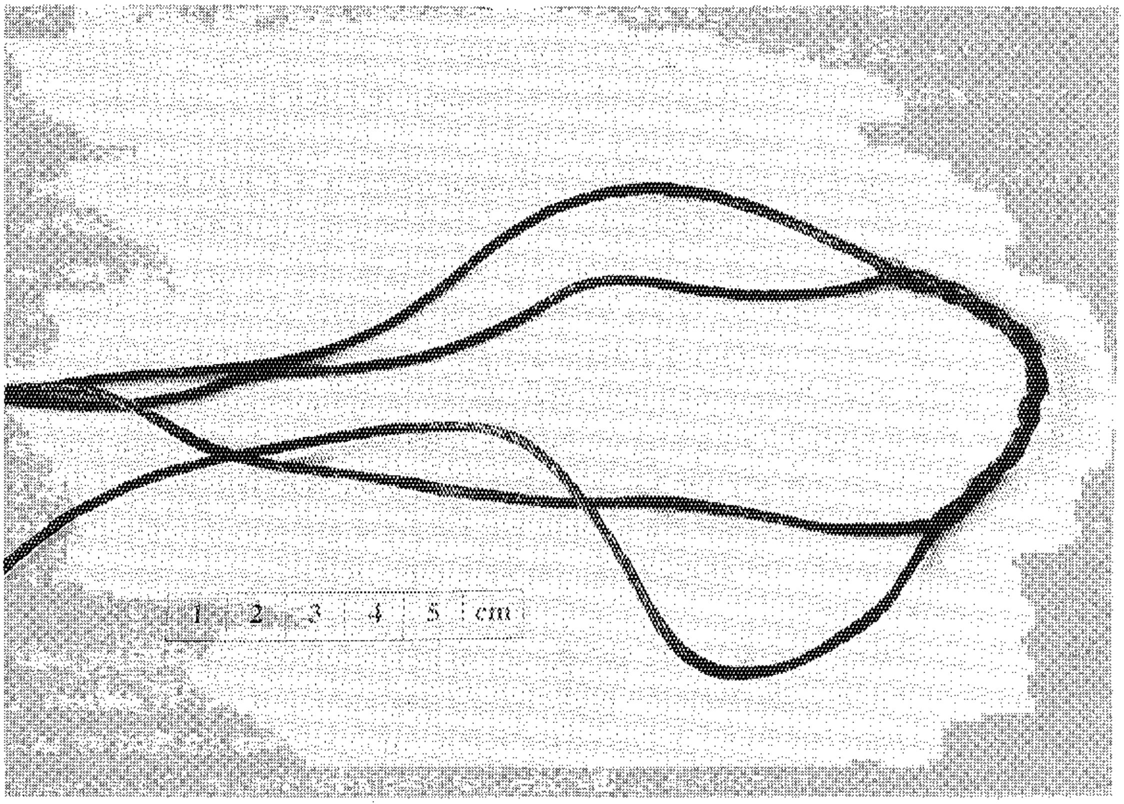


Figure 14 Noise resistor and signal lines of graphite cord.

6 APPLICATIONS OF NT AND TC-NT SENSORS

Noise thermometry, as a complex method, is employed especially in areas where its exceptional characteristics (no decalibration or drift and high absolute accuracy) are required[+]. The high costs of the electronic device may be seen in relative terms, however, if combined sensors are used ; only one such device is then necessary for recalibrating any number of sensors from time to time.

6.1 Applications in the Laboratory and Industrial Plants

It is well known that in nuclear reactors thermocouples and resistance thermometers undergo decalibrations and exactly in such plants accurate and reliable measurements are necessary over long periods. Therefore, NT and combined TC-NT in addition to RT-NT sensors, in which the TCs and RTs are recalibrated in situ, have been used here (see also Table 1) [18, 19, 21, 22, 30, 41, 43-48, 61-63]. With the application of remote preamplifiers the measurement signals could be transmitted over distances of 150m [61] and 600m [62] to the control room.

A wide field of application for noise sensors is to be found in the high-temperature range (>1000℃), since at these temperatures any sensor exhibits drifts. Combined TC-NT sensors have been used here for basic investigations of other temperature sensors, eg, drift tests of WRe and B_4C/C TC_s as a function of the insulation material and pressure [7]. Noise sensors are also useful when material data or process parameters are to be determined in the high-temperature range, since here exact information about the temperature is essential. If they are applied in plants operated with high a.c. currents, eg, hot isostatic pressure (HIP) plants [7], ferromagnetic materials have to be avoided in the signal lines (see Section 4.3). Other fields of application are metal and glass melts and chemical and petrochemical plants (see Table 1), if economic profit can be expected (eg, by higher yields from a process) by precise temperature measurement.

Table 1 gives a survey of sensor data and conditions of employment. It gives an indication of the numerous possible variations for applying NT and combined TC-NT sensors. In all cases accurate, undisturbed transmission of the measured signal was checked by selecting various frequency bands and 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 under plant conditions.

In the following some detail are given concerning table 1.

[+] See,eg,[81,82,83,84].

Noise thermometry had also been applied by ERNO Raumfahrttechnik, Bremen, for the calibration of the furnace high temperature measurement system (up to 1850℃) of the German D2-mission on SPACELAB in early 1993.

Table 1 Examples of sensor data and conditions of employment of NT and TC-NT sensors (RPA, Remote PreAmplifier; KWO and GKN, pressurized water reactors with 350 and 850 MW_{el}; AVR, high-temperature experimental reactor, 15 MW_{el}).

Plant	Sensor				Transmission cable		
	NT-TC	R_S	Mineral-insulated cable				
	(materials)	(cold) (Ω)	Ø (mm)	Length (m)	Length (m)	Impedance (Ω)	T (°C)
KWO Obrigheim (core region)	NiCr20	25; 46	2	9	15 (+20 test)	50; 120	310
GKN Neckarwestheim (primary circuit)	NiCr30-NiCr/Ni	50	6	0.4	10–50; RPA: 200	125	320
AVR Jülich (top reflector)	NiCr20-NiCr/Ni	25	3; 6	3	20–30; RPA: 600	50	700–1150
Methane reforming plant (He heater)	NiCr20-NiCr/Ni	17	4; 6	3	10	35	1000
Liquid air plant	NiCr20	120; 300			6	150	−170
Molten glass	PtRh30-PtRh30/PtRh6	7; 10	1 m Al_2O_3 tube, 15 mm Ø		5 (+20 test)	35; 50	1200–1400
HIP plant	WRe26-WRe5/WRe26	2	0.5–1 m in W tube of 7 mm Ø		3	20	1000–2000

In order to provide practical evidence of the noise thermometer's theoretical independence of a nuclear reactor's ambient conditions, namely at high neutron and gamma radiation, several noise thermometers were tested in research reactor FR-2 at Jülich. The thermal neutron flux at the location of the sensor amounted to approx. 10^{14} neutrons cm^{-2} sec^{-1} and the gamma flux $5 \cdot 10^8$ roentgen/hour. The noise sensors were irradiated for several months, in the cource of which one resistance value, for example, changed from 57 ohms to 61 ohms. This did not of course impair the efficiency. All temperatures measured with noise thermometers were within the calibration accuracy of ±0.5% of the reference thremocouples, reliable in the short term.

Further noise temperature measurements were successfully carried out under power reactor operating conditions in the nuclear power station at Obrigheim (in-core measurements).

The adequacy of noise thermometry for measuring low temperatures was shown at a petrochemical firm's large-scale liquid air plant. The resistance thermometers usually employed there provided different temperature values. For this reason two noise sensors were applied and the temperatures accurately determined to -170℃.

The noise thermometer' s suitability for precise temperature measurement in molten glass was successfully demonstrated in an industrial manufacturing firm. A combined thermocouple - noise thermometer with PtRh10/Pt thermocouples and a noise resistor made of PtRh30 was employed.

A further demonstration measurement in an oil- or gas-fired power station of 500 MW, namely in the live steam line, provided accurate results with combined noise sensors.

In spring 1977 several combined thermometers were installed in the top reflector of the experimental high - temperature nuclear power station in Jülich for long - term sensor trials under the conditions of a high-temperature reactor. All the noise sensors have proved themselves reliable (see also Section 6.1.1).

Twelve combined NiCr/Ni TC-NT's were installed in the immediate vicinity of the electrically heated helium heater (power 10 MW, maximum 38000 A DC) in a methane reforming demonstration plant in the KFA Jülich (EVA Ⅱ). The extremely high electromagnetic interference fields generated by the rectifier plant (3-phase transductor controlled rectification) brought about considerable interference spikes superimposed on the noise sensor's signal. They were eliminated with the aid of the measures described in Section 2.6 . In this methane reforming plant - just as in a further semi-commercial experimental plant for coal gasification - the precise measurement of the absolute temperature of the hot heliun (approx. 950℃) was decisively important for the experiment's success. This task was mastered by recalibrating the thermocouples in situ.

Problems in temperature measurements occur at many locations in large-scale industrial petrochemical plants which cannot be satisfactorily solved with the thermocouples previously employed there. For example hydrogen, which frequently occurs here, leads to considerable, unforeseeable drifts in the thermocouples' e.m.f. Optimization of the process nevertheless requires precise knowledge of the absolute temperature. For this reason measurements with combined TC-NT' s were carried out in several of these plants in the range between 750 and

900℃ with an accuracy of 0.1 . . . 0.2%. Combined NiCr/Ni TC-NT' s have been applied in the cracking furnaces of a large-scale ethylene plant (200 t naphtha per h) at several locations under industrial conditions. The thermocouples were here recalibrated every three months as a matter of routine by means of the noise resistors.

Apart from the measurement in the liquid air plant, the sensors were connected to the amplifiers by matched plastic cables. At the connection to the mineral insulated lines, the thermocouple signals can be switched to the extension cables by means of a change-over switch and thus the impedance load imposed on the transmission cable to the noise electronic apparatus by the in part very long extension cables (100 m and over) avoided. (Another possibility is the utilization of matched extension cables. There is thus no need for an additional transmission cable.)

A further simple solution is to measure the temperature of the cold end of the sensor by a Pt 100 resistor (cold junction of the TC, see Figure 5) ; the TC and NT singles can then be transmitted over the same matched (for NT) 4-wire copper cable.

6.1.1 Noise Temperature Measurement in the Top Reflector of the AVR Reactor at KFA Jülich

Two combined TC-NT sensors were positioned in a test set in the top reflector of the AVR reactor in 1984 for long-term tests (NiCr/Ni TC; 80Ni 20Cr noise resistor) [75]. This was a type of standard sensor for use in HTR plants - having evolved from previous developments and tests at the AVR reactor. These sensors corresponded to the requirements made by the PNP (nuclear process heat prototype plant) with respect to sheath material (Incoloy 800), geometric dimensions (diameter 6 mm) and the requirements made on insulation resistance so that they may be applied in hot zones.

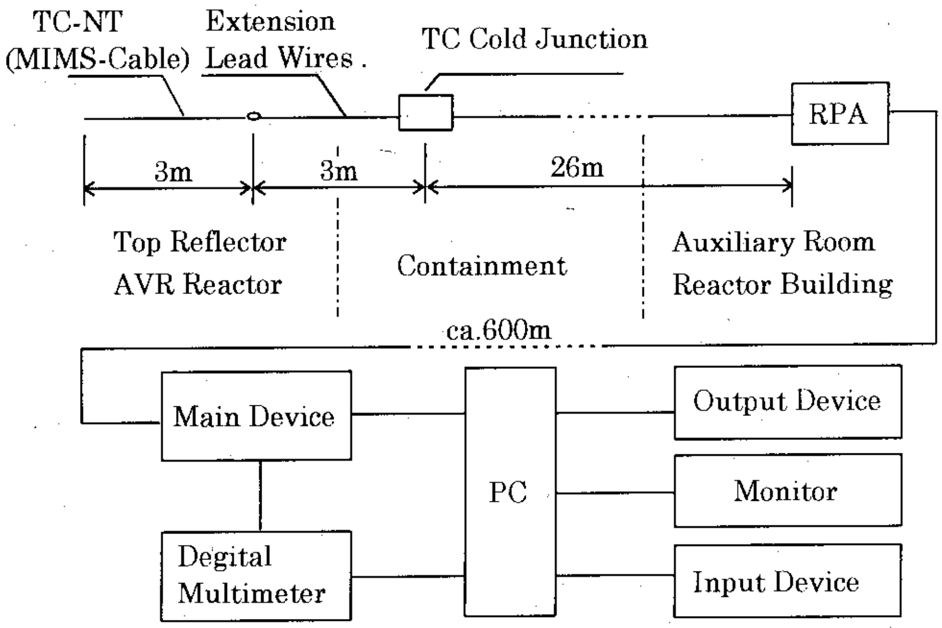
A new electronic NT system was installed at the AVR reactor in early 1987 (Figure 15). This system had been developed with respect to case of handling and operational safety.

A " remote preamplifier " (rpa) was located in the auxiliary room previously used for performing the measurements. It comprised the following important components : the reference source. pre-amplifier and booster amplifier as well as a control unit. The sensor and reference signals amplified up to the volt range could now be transmitted largely without difficulty across great distances to easily accessible locations ; in the present case across approx. 600 m to the IRE test laboratory at the KFA. The main device with the control unit for the rpa was situated here.

Noise temperature measurements had been carried out with the measuring arrangement described here since mid-1987 and the thremocouples in the combined sensors thus recalibrated in situ (Figure 16).

Depending on the temperature profile (as a function of the operational state of the reactor) the readings of the TC 's were somewhat more than the 1 DIN tolerance (0.75 %) above (as in Figure 16) or below the standard values (errors of the second kind).

The change in the e.m.f of the thermocouples was caused 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.



Laboratory of the Institute of Reactor Development

Figure 15 TC-NT Instrumentation at AVR Reactor

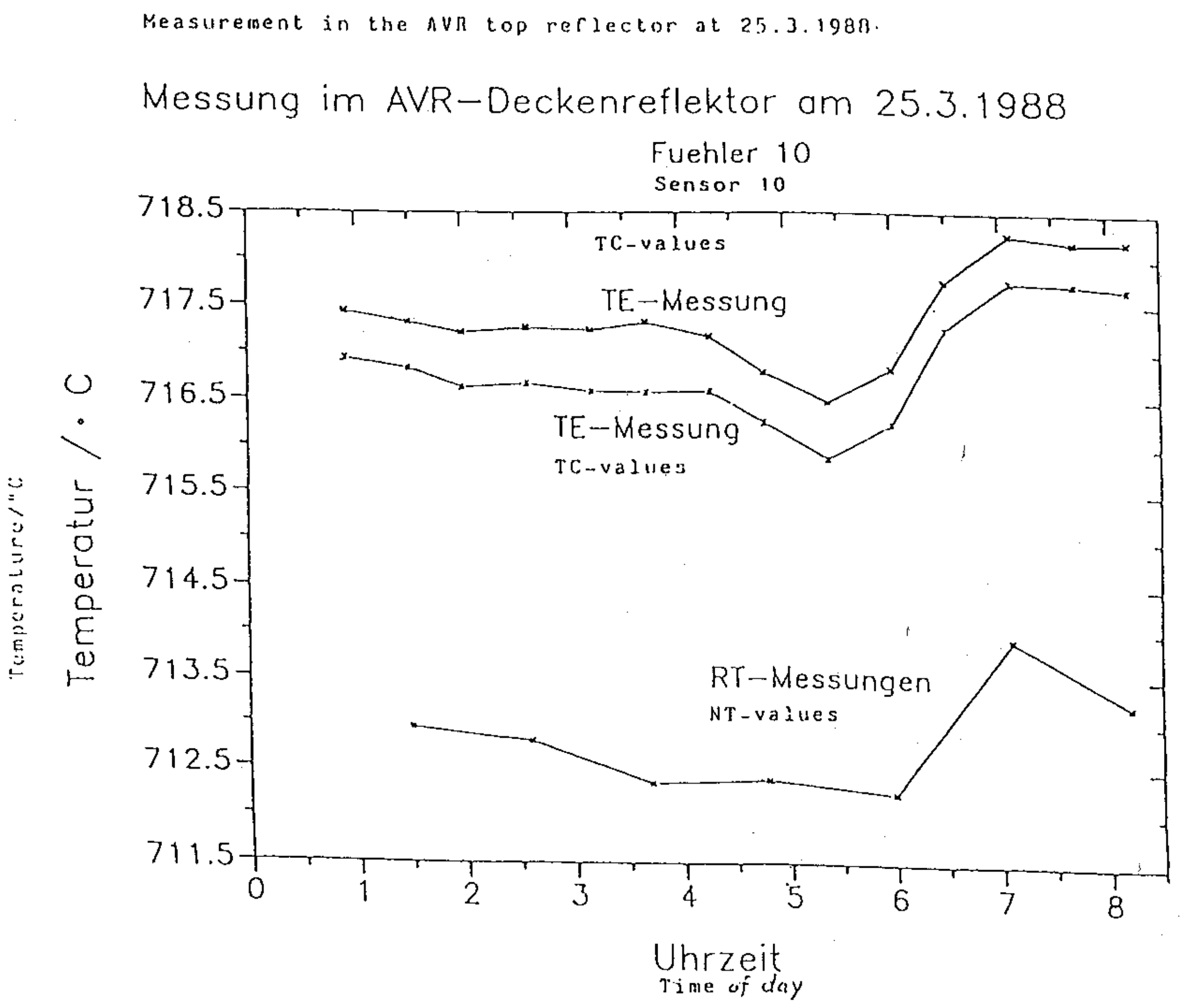


Figure 16 Automated temperature measurement in AVR-reactor with a combined sensor : in situ calibration of thermocouples.

6.1.2 Noise Thermometry in Commercial Nuclear Power Plants

6.1.2.1 Noise Thermometry in a German Nuclear Power Plant

In the 850 MW (electric) pressurized water reactor plant GKN-Neckar 1, noise thermometry is applied as a reference and calibration method [53, 76].

Three combined sensors (2 type N TC-NT, 1 type K TC-NT) are installed in the primary circuit (one sensor in each of the three loops).

The noise and TC signals are transmitted by carefully matched cables (15 m, 20 m, 8 m, respectively) [52] to 3 remote preamplifiers (rpa) in transducer rooms and from there over a distance of approx. 200 m to a room adjacent to the control room. The main device with the control unit for the rpa is situated here (see Figure 5).

Figure 17 shows measurement results from loop 1 over 75 h (abscissa : time of day) in the frequency band 20-200 kHz, which was completely free of EMI. The averaging time for one measurement point was 50 min. The theoretical statistical uncertainty was ca. ±0.1 K for 1 σ, which fits well with the experimental statistical uncertainty shown in Figure 17.

The averaged valued for the NT and both TC 's over 75 h are shown in the upper right-hand corner. The difference $\bar{T}_{TC} - \bar{T}_{NT}$ gives the deviation of the TC from the true absolute temperature and consequently a recalibration of the TC. The estimated total error of this remote and in-situ calibration is less than ±0.3 K. It consists primarily of the signal transmission error, the error of the reference temperature and possible small undetected EMI, the frequency and time domain having been checked in the way described above. The statistical error (over 75 h) is negligible here (±0.01 K). The uncertainty of the difference $\bar{T}_{TC} - \bar{T}_{NT}$ is ca. ±0.01 K. Figure 17 also shows the sensor resistance over time (resistance material: 30%Ni-20%Cr).

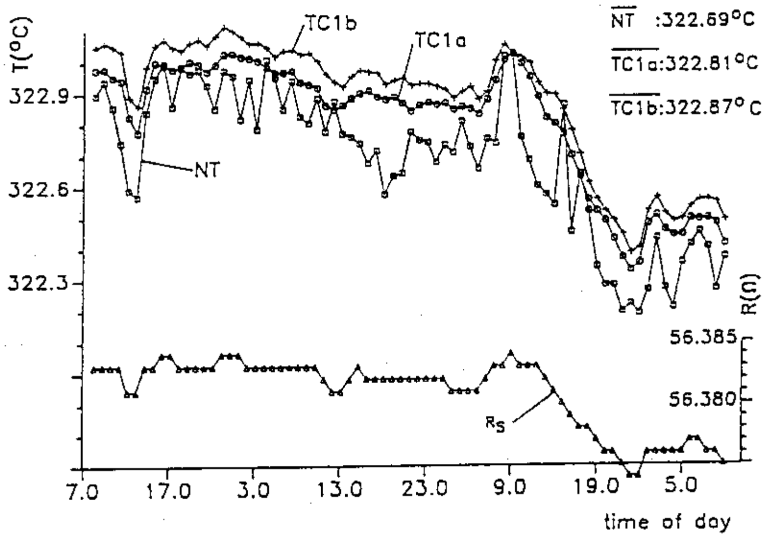


Figure 17 Noise and TC temperatures of a combined sensor in a nuclear power plant (also shown : noise resistance R_S)

The emf of the mineral-insulated metal-sheathed type N thermocouple cable used for the combined sensor in loop 1 is very close to the standard reference values, as Figure 17 reveals.

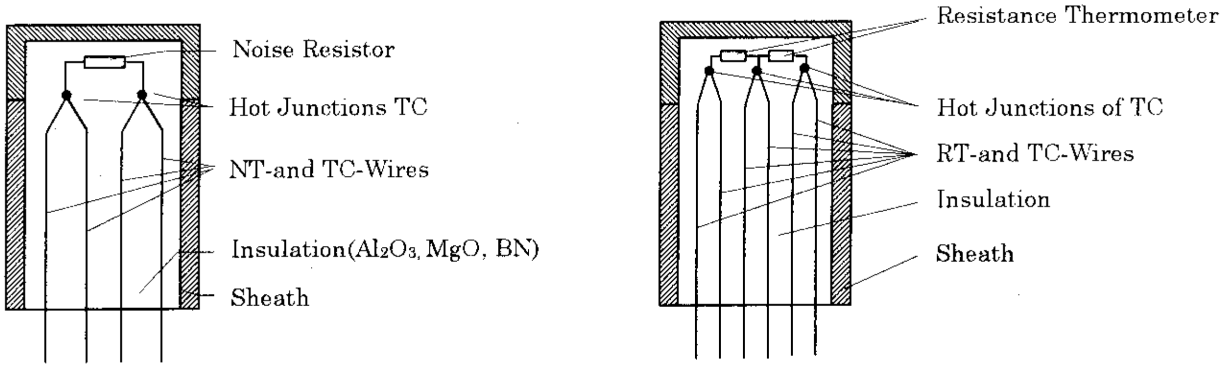
The noise thermometers in loop 2 and 3 show EMI in the low and high frequency range so that only reduced bandwidths, 50 to 80 kHz and 70 to 100 kHz respectively, can be used. However, as very long averaging times are available, comparable accuracies to loop 1 are attained.

The long-term testing of the three TC-NT measurement systems at GKN 1 will provide information to improve handing of the system by the control room staff ; this is necessary because noise thermometry is a relatively complex measuring method.

6.1.2.2 Noise Thermometry in a WWER 440 Nuclear Reactor

Experimental arrangement

The applicability of noise thermometry had been demonstrated at unit 2 of the V-1 Bohunice nuclear power plant in the Slovakia Republic under operating conditions [71]. At this WWER 440 pressurized water reactor two combined thermocouple-noise thermometer sensors (TC-NT sensors, Figure 18, left side) of type N were installed in the hot and cold part, respectively, of loop 1 in the primary circuit.



Combined thermocoupele-noise thermometer sensor (TC-NT sensor)

Combined thermocouple-resistance thermometer sensor (TC-NT sensor)

Figure 18 Combined TC-NT and TC-RT sensors for WWER 440.

Combined thermocouple-resistance thermometers (TC-RT sensor, Figure 18, right side) of the reactor instrumentation (VUJE system) were installed close to the TC-NT sensors. It was therefore possible to measure the temperature by three different methods.

The noise and TC signals of the TC-NT sensors were transmitted by matched cables (21 m, 23 m) to a remote preamplifier (rpa) in a cable room and from there over a distance of approx. 100 m to a room adjacent to the control room. The main device with the control unit for the rpa was situated here (Figure 5).

Measurement results

As an example Figure 19 shows noise measurement results from the TC-NT sensor in the hot part over 24 h (abscissa : time of day) in the frequency band 20-60 kHz, which was completely free of EMI (electromagnetic interferences).

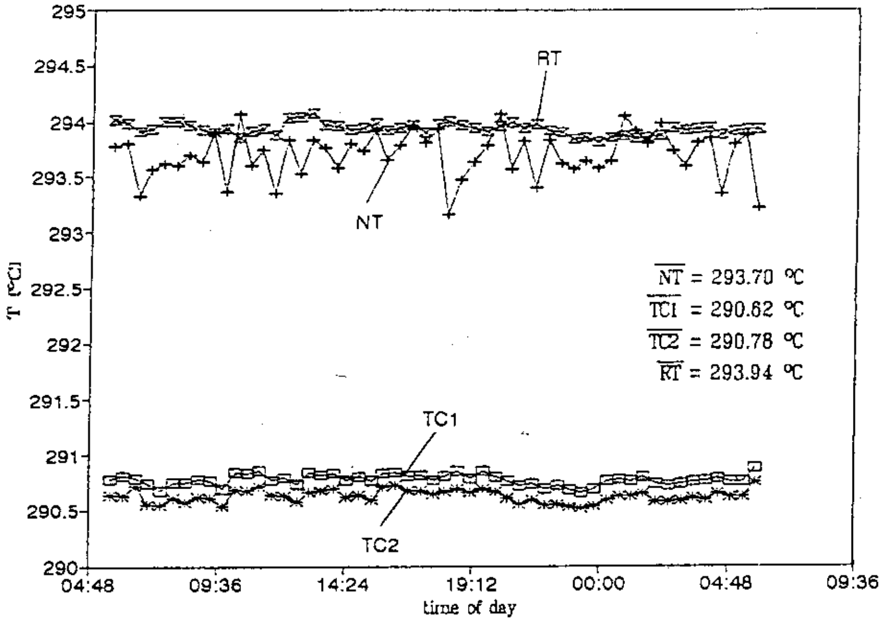


Figure 19 Noise (NT) and thermocouple (TC) temperatures of a combined sensor in a WWER 440 nuclear reactor and the resistance thermometer reading (RT) of the reactor instrumentation.

The averaging time for one measurement point was 1600 sec. The theoretical statistical uncertainty was approx. ±0.2 K for 1 σ, which fits well with the experimental statistical uncertainty shown in the figure. The figure also shows the simultaneously measured values of a resistance thermometer from the TC-RT sensor of the reactor instrumentation installed nearby.

The averaged values for the NT, both TC 's and the RT over 24 h are shown in the right-hand part of the figure. The differences T_{TC}-T_{NT} and T_{RT}-T_{NT} give the deviation of the TC and RT from the true absolute temperature and consequently a recalibration of the TC and RT. The estimated total error of this remote and in-situ calibration in less than ±0.3 K.

Apart from the statistical error, which can be made indefinitely small by using long measuring time, three individual errors make major contribution to the overall error :

- Transmission error for the sensor signal.
  As indicated by measurements with the upper band limits of 110 kHz, 90 kHz and 60 kHz, the transmission error in the 20-60 kHz frequency band was < 0.1 K.
- The reference temperature error (46℃) is < 0.05 K. An uncertainty of < 0.1 K thus follows for the measuring temperature.
- Error due to possible small, undetected external interference signals (EMI).

> Verifying the noise signals in the time and frequency range ensured that errors due to external interference signals are $< 2.10^{-4}$ corresponding to < 0.1K (see Section 6.1.3.2, Figure 28). The reproducibility of the measured values (relative accuracy) is considerably higher than the absolute accuracy. In this case, the transmission error and the reference temperature error are no longer applicable, in the same way as the error due to possible small undetected external interference signals, if the latter are constant. Only the statistical error for reproducibility remains, which, however, - as already mentioned above - can be made indefinitely small by long measuring times.

The statistical error (over 24 h) is negligible here (± 0.03 K) .The uncertainty of the difference T_{TC}-T_{NT} and T_{RT}-T_{NT} is approx. ±0.03 K.

The whole automated measuring procedure of the TC-NT system was controlled by a computer and handled by the control room staff.

The good agreement between the value of the resistance thermometer and the noise thermometer (Δ T = 0.24 K) shows that the resistance thermometer was carefully calibrated before use. The difference between the thermocouples and the noise thermometer (Δ T = -3K) gives the deviation of the thermocouple batch used here from standard values.

Conclusions from Section 6.1.1 and 6.1.2

The results show that noise thermometry can be used as a reference method with high accuracy for the in-situ calibration and recalibration of temperature sensors in large nuclear power plants.

Since the sensor may be randomly altered in noise thermometry, ie, noise thermometry does not display any drift problems, this method is also particularly suitable as an accident instrumentation since other temperature sensors, for example thermocouples, generally display large errors if exposed to elevated temperatures (see also Section 6.1.3.1, Figure 27).

6.1.3 Temperature Measurement in the High-Temperature Range (1000-2000℃) by Means of Noise Thermometry

Particularly at high temperatures (1000-2000℃), any sensor undergoes changes with time because of the high temperature itself. This is especially true of measurements under industrial conditions, where, for example, high-temperature thermocouples (TCs) may show large drifts. The extent of the drifts depends on the conditions under which the TCs are used ; ie, on the temperature itself, the time of operation, the furnace materials and charges, the atmosphere, and the insulation and sheath materials of the TCs [76,78,79]. (Radiation pyrometry is also often impaired by high temperature as, for example, the emissivity can change.)

6.1.3.1 Basic Investigations of W-Re Thermocouples in the High-Temperature Range

It is known from the literature [80] that adequately aged W-Re thermocouples exhibit a stable thermovoltage under extremely clean conditions a 1800℃ for 2000h, although on these occasions no checks were made for inhomogeneity errors of the second kind.$^+$

In conventional industrial plants, however, the thermopower of TCs may drift rapidly. The investigations were therefore performed under conditions as prevail in such plants (eg, in hot isostatic pressing (HIP) plants, sintering furnaces, etc) with a graphite heater, ie, in a carbon environment .

A typical HIP sensor with an integrated noise resistor (combined TC-NT sensor) was tested in a high-temperature furnace with a graphite heater : WRe5/WRe26 TC wires of 0.5mm ∅, insulation beads of BN with a B_2O_3 content of approx. 0.1%, sheath (protection tube) of high purity graphite; WRe26 noise resistor with 2.5 Ω resistance at 300 K, Ar atmoshere of 100kPa (see Figures 7 and 11).

Figure 20 shows measurement results at the beginning of the experiment at 1500℃. The high-temperature furnace was operated at constant power (without temparature control), and the noise thermometer indicated that the temperature was constant. The measured points of the two thermocouples illustrate the emf drift over time (on the abscissa : time of day).

The positive deviation of ~ + 12 K at the beginning, which corresponds to the error of this special WRe5/WRe26 wire batch in the as-received state, changed into a negative deviation of ~ −20 K after 66 h of operation; the indicated errors of the two thermocouples showed a slightly different development. Short-time variations in the furnace temperature, mainly caused by temporary mains fluctuations, were found as correlated signals in the noise temperature and the thermocouple temperatures. The statistical uncertainty (for 1 standard deviation) of the individual noise temperature values which, in the same way as the thermocouple value, were recorded every 30 min, was in the region of 0.6K.

[+] For practical reasons, a distinction is made between inhomogeneity errors of the first and second kind. Errors of the first kind arise if the temperature gradient along the thermowires does not change (ie, if the position of the TC in the temperature gradient in which the inhomogeneties were generated, and/or the temperature profile, does not change). Error of the second kind arise if the temperature gradient along thermowires varies (owing to a change in the temperature gradient at constant position of the TC or by variation of the position of the TC at constant temperature gradients).

Both types of error have the same causes. It is meaningful to distinguish between them 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 TC in a different temperature profile. Errors of the second kind are generally much larger than errors of the first kind.

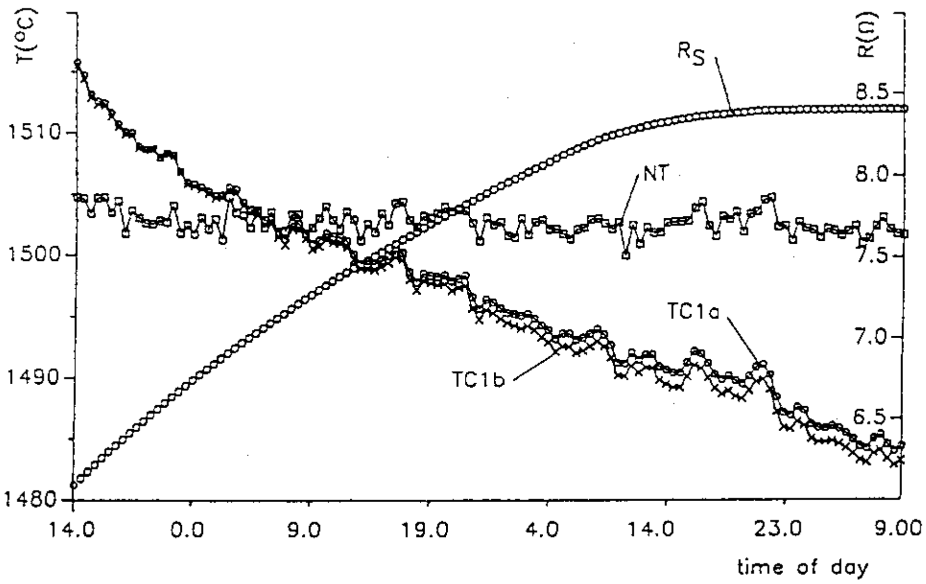


Figure 20 Driit of the two thermocouples of a combined WRe sensor under typical HIP operating conditions at 1500℃ (error of the first kind). Insulation material: BN; sheath: graphite tube. Also shown: Time dependent change of the noise resistance,R_s.

Figure 20 shows the errors to be expected for ordinary TC sensors in HIP plants even at 1500℃ .

During the 66-h, constant-temperature measurement illustrated in Figure 20, the value of the noise resistance changed by approx. 40%. The results show that the noise temperature measurement was not affected even by these considerable and relatively fast changes of the sensor because the respective actual noise resistance is used for temperature determination at correspondingly short time intervals. This independence of sensor change is an exclusive feature of noise thermometry as compared to other methods of temperature measurement.

The investigations were carried out to temperatures as high as 1900℃, demonstrating corresponfingly faster decalibrations of the TC at the elevated temperatures (Figure 21).

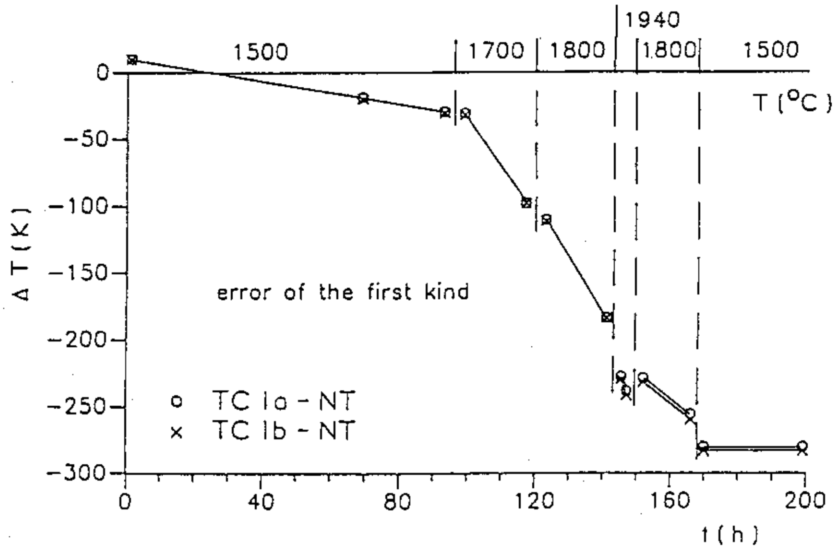


Figure 21 Deviations of the two thermocouples of the combined WRe sensor from Figure

20 as functions of time and temperature. Insulation material: BN; sheath: graphite tube ($\Delta T=T_{TC} - T_{NT}$).

After an operating time of 200 h (including 4.5 h at 1920℃) the deviation was finally found to be ~ 300 K at 1500 ℃.

Figure 22 shows the results of a combined sensor of identical construction (WRe5/26 TC wires of 0.5 mm ∅; WRe26 noise resistor), but with PBN (pyrolytic BN) insulation and a W protection tube. The emf is nearly stable at 1500℃ over 60 h. Drift errors do occur, however, at 1800℃ and above.

Figure 23 shows the quasi-continuous registration (similar to figure 20) of the emf drift over 17 h at 2000℃ of the sensor from Figure 22.

Figure 20 to 23 show the inhomogeneity error of the first kind ; ie the temperature gradient along the TC wires was not changed. Since the temperature gradient in HIP facilities is changed with pressure changes, the errors to be expected in this case can be considerably higher (error of the second kind ; see also Figure 25 below) ; the figures show that clean insulation (PBN) and compatible sheath material (W) result in smaller deviations of the TC.

Even better results were obtained with an identical sensor (as in Figure 22), however, with Al_2O_3 insulation (purity > 99.7%). Figure 24 shows the high constancy of the thermovoltage over long periods of time, between 1500 and 1700℃. However, this only applies to the error of the first kind.

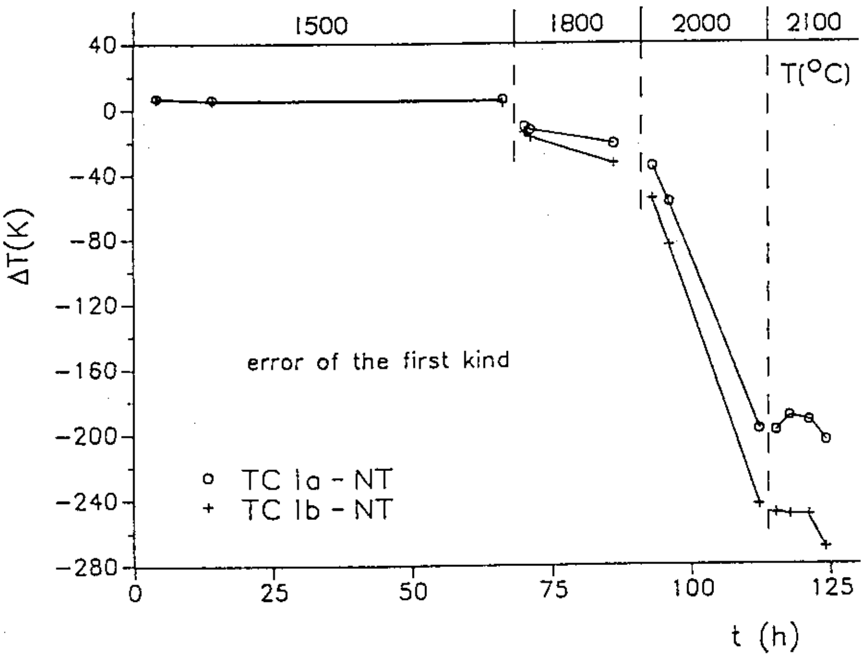


Figure 22 Deviations of the two thermocouples of a combined WRe sensor as functions of time and temperature. Insulation material: PBN; sheath: W tube.

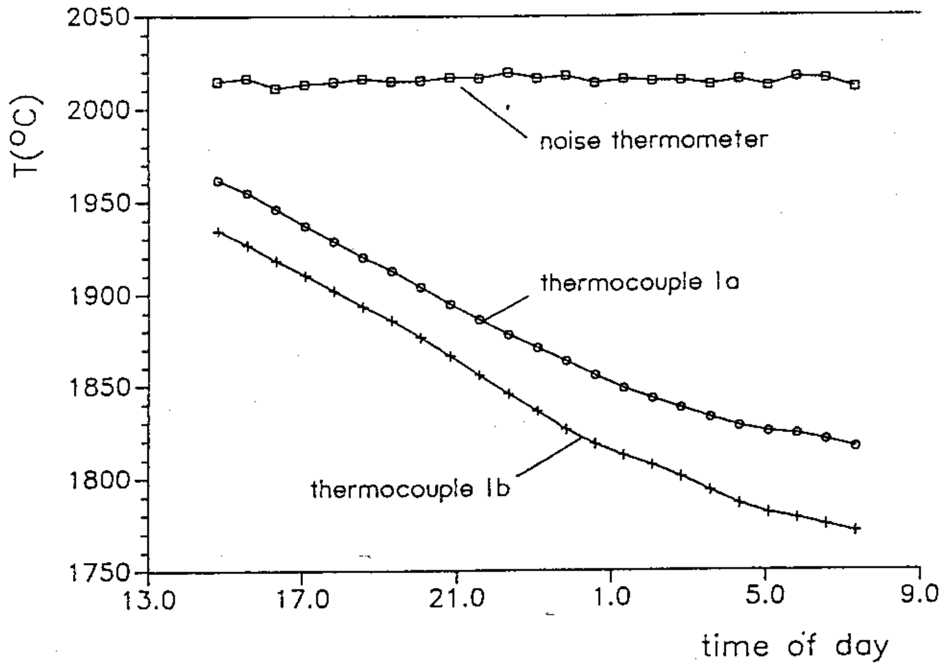


Figure 23 Drift of the two thermocouples of the combined WRe sensor from Figure 22 at 2000℃ (error of the first kind). Insulation material: PBN; sheath: W tube.

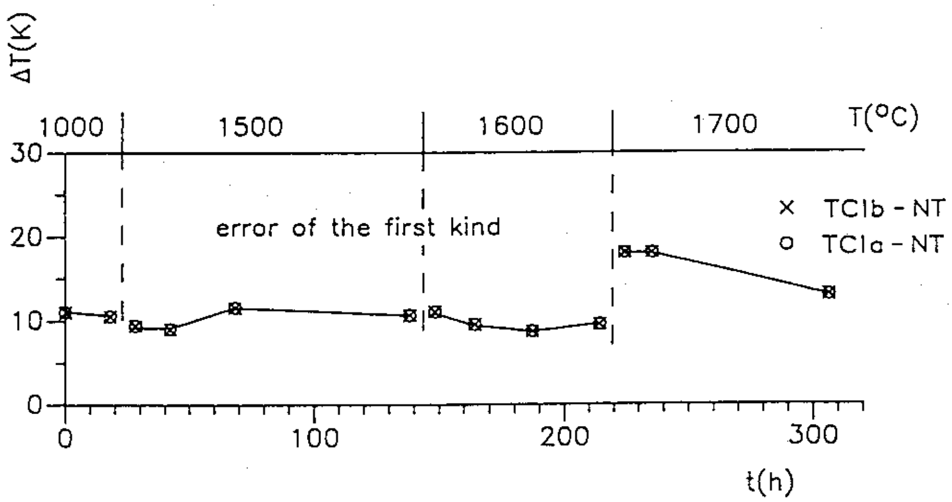


Figure 24 Deviations of the two thermocouples of a combined WRe sensor as functions of time and temperature .Insulation material: Al_2O_3; sheath: W tube.

Figure 25 gives the deviations of the same TC for a position change in the temperature profile, where the TC was drawn out of the furnace up to 200 mm after the last measured point at 1700℃. At 200 mm the holding time was 40 h. The great deviations show that the thermowires had already become largely inhomogeneous in the hot region of the furnace; ie, the thermopower had changed considerably.

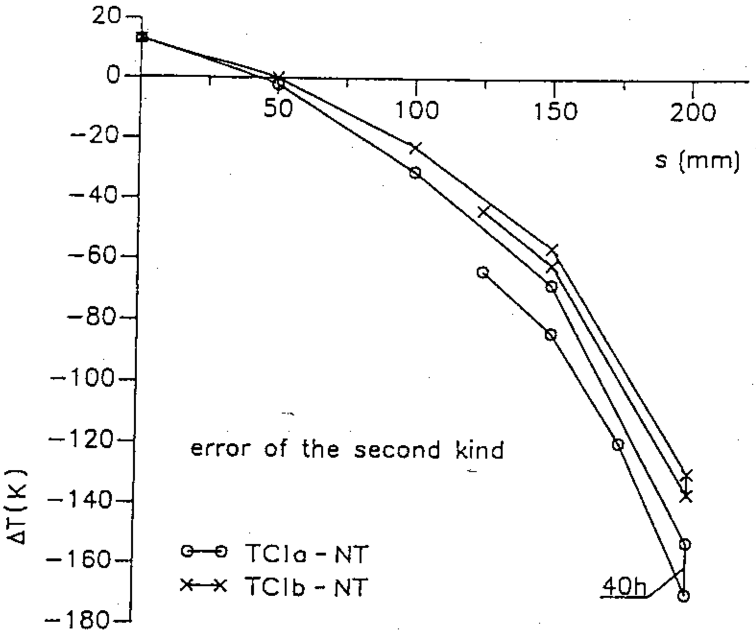


Figure 25 Deviations of the WRe thermocouple from Figure 24 at 1700℃ as a function of the position in the temperature gradient of the furnace.

Figure 24 and 25 illustrate that particular attention must be paid to inhomogeneity errors of the second kind. This error can occur in HIP plants, eg, in connection with pressure variations; ie, without a position change of the sensor (as stated above). The relatively small deviations of emf (with regard to errors of the first kind) of a sensor with Al_2O_3 insulation and W protection tube are also demonstrated in Figure 26. The behaviour of the TC is good up to ca. 1900℃, even with temperature cycles.

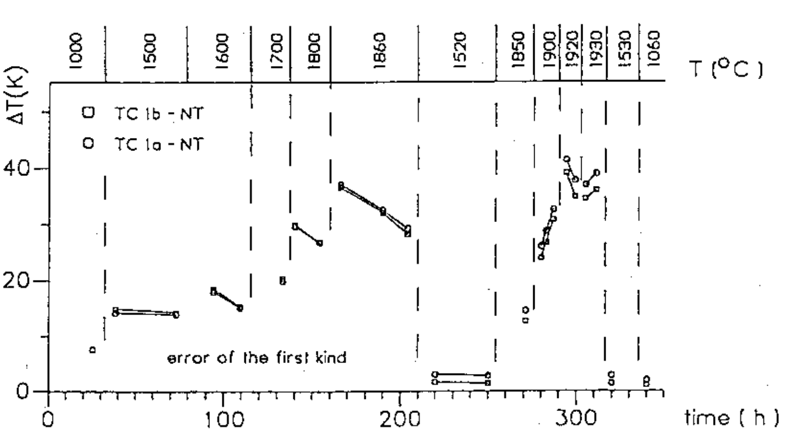


Figure 26 Deviations of the two thermocouples of a combined WRe sensor as functions of time and temperature. Insulation material: Al_2O_3; sheath: W tube.

Sensors with pure Al_2O_3 insulation show a better stability of emf than with BN insulation, as Figures 24, 26 and 22, 23 reveal, but Al_2O_3 can be used only up to approx. 1900℃, BN however, up to about 2200℃.

The (calibrated) TC-indication is normally used for the measurement of temparature changes, especially fast changes, because the NT-indication needs more time due to necessary averaging of the noise voltages (Section 2.4). If, however, the thermowires exhibit strong inhomogeneities, the NT-indication should be preferred.

Figure 27 shows measured values obtained with a sensor, similar to that of Figure 22, when performing temperature cycles between 1000 and 2000℃ after the sensor has been exposed for some time to temperatures of up to 2100℃. The TCs show temperature values in the whole range which are too low by several hundred K. As the temperature changes are not particularly fast here, the NT values give the true temperature variation with good accuracy (total measuring time for one NT value : 200 s).

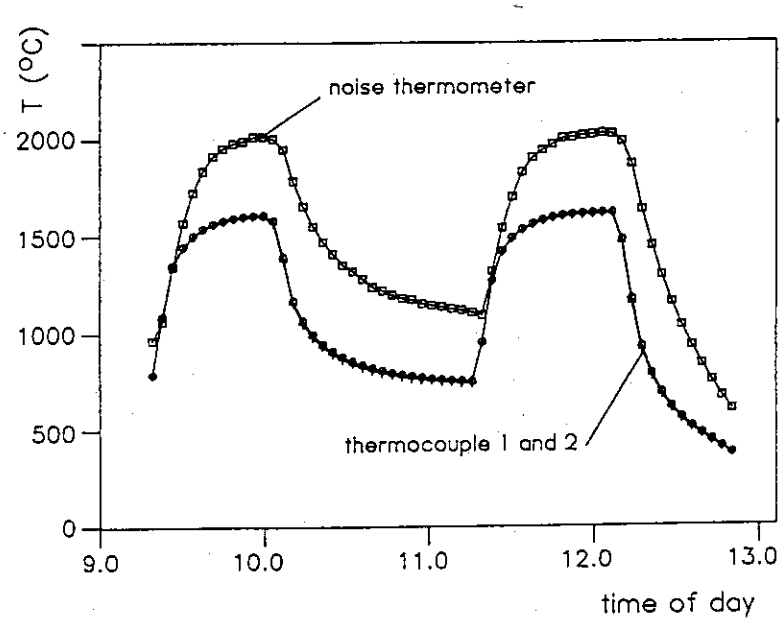


Figure 27 Temperature cycles with a combined sensor after operation at high temperatures : The TC values are several hundred K too low.

The combined sensor in Figure 27 had been exposed to high temperatures for some time . Similarly high temperatures of more than 2000℃ occurred during the LOFT project in an experiment on a loss of coolant accident with partial meltdown of core components (analogous to TMI-2). The results of Figure 23 and 27 show that combined sensors also have advantages when used in accident instrumentation since in general TCs display large, no longer tolerable drift errors if they have been exposed to very high temperatures.

Conclusions

The investigations have shown that the TC drift can be quite different depending on the operating conditions (temperature, insulation and sheath material, etc.). Correspondingly, recalibrations by noise temperature have to be performed at shorter or longer time intervals. When the temperature profile changes along the thermowires then a recalibration is necessary in any case (because of the errors of the second kind). A quasi-continuous NT-indication can be advantageous, as Figure 27 shows, if time-dependent temperature changes are performed, provided they are not too fast.

6.1.3.2 An Example of Electro-Magnetic Interferences

Generally, the most severe problem for noise thermometry in both industrial plants and the laboratory is the detection and the avoidance or rejection of EMI (electro-magnetic interferences), as stated in Section 2.6.

Both possibilities of detecting and eliminating EMI, ie, in the frequency and time domain, have been applied for the measurements reported here.

The experiment described in Figures 20 and 21 revealed interferences in the frequency domain which illustrate the high sensitivity of narrow-band interference detection. Figure 28 shows the "temperatue spectrum" [53,54] (sensor power spectrum related point-by-point to the reference spectrum during balancing, multiplied by the corresponding measured values of the sensor and reference resistor and the reference temperature : $T_R \cdot R_R/R_S$) at 1800℃ between 20 and 200kHz, plotted in 450 points each with 400 Hz bandwidth. The spectra were calculated by a Fast Fourier Transform (FFT) Analyser. The averaging time for the sensor and reference spectrum was 1000 s in each case (theoretical statistical uncertainty for 1 σ : ±10K for the individual frequency point).

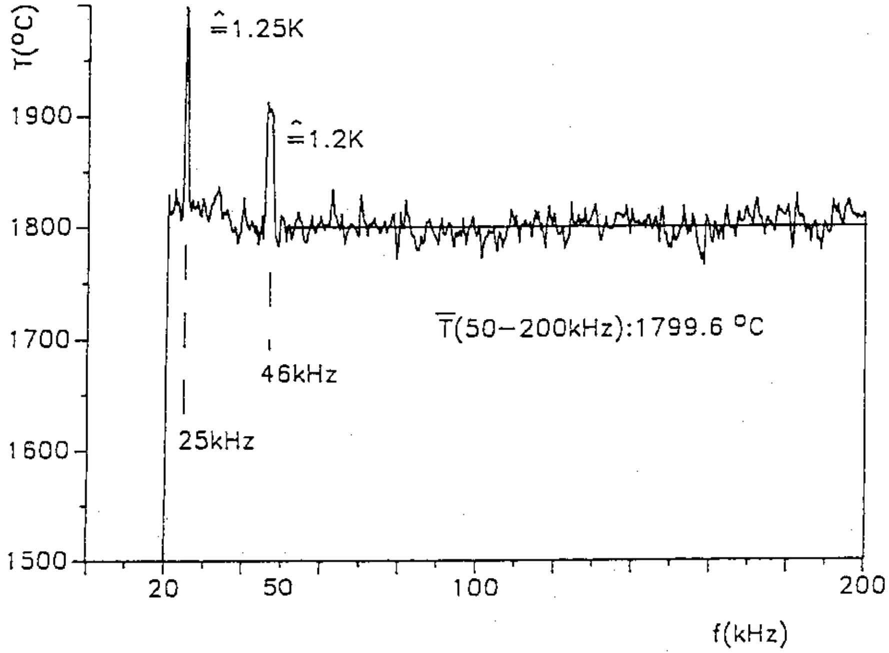


Figure 28 Temperature spectrum with narrow-band interferences.

Two interference peaks at 25 kHz and 46 kHz are clearly visible in the low-frequency part of the spectrum; they cause a distortion in noise temperature of 1.25 K and 1.2 K, respectively. A comparison of the interference peaks with the statistical fluctuations in Figure 28 suggests that the averaging time used would still be sufficient to detect narrow-band interferences corresponding to a relative error of 1 to 2×10^{-4} the noise temperature. If the averaging time for the sensor spectrum is prolonged, the sensitivity of narrow-band interference detection can thus be still further increased.

Every individual frequency point in Figure 28 provides a noise temperature which, however, exhibits a high statistical uncertainty due to the small bandwidth (400 Hz); this uncertainty can be reduced by integration over several points. Since narrow-band frequency ranges with interferences are clearly visible, it is easy to obtain the undistorted noise temperature by integration of the undisturbed frequency points; in the time domain this can only be achieved by complicated filtering. Figure 28 provides the noise temperature for integration over the clean range from 50 to 200 kHz at 1799.6℃ with a statistical uncertainty of ±0.5 K.

There are also methods of interference detection and elimination in the time domain (eg, automated blanking of disturbed time intervals). The long-term objective for both ranges is a maximum automation of interference detection and elimination, and their integration into the measuring procedure.

Generally, the problem of interference rejection is different for each measuring task and must therefore be solved individually each time.

6.1.3.3 Investigation of the B4C/C Thermocouple

The B_4C/C thermocouple was developed for the high-temperature range up to 2200℃. Typical applications are in high-temperature plants ; eg, in sintering furnaces, hot presses, and HIP plants. The advantage of the B_4C/C TC over metallic TCs (eg, the WRe TC) has been seen primarily in the low or nearly negligible drift in the emf at high temperatures, owing to the chemical stability of the TC conductors B_4C and C in an adequate environment.

To check this assumption, a B_4C/C TC was investigated and calibrated via noise temperature measurements (with the use of a combined WRe TC-NT) in an HIP plant in the range 1000 - 1800 ℃. Figure 29 shows the results of this in situ calibration (pressure : 500 bar). The reference range specified by the manufacturer of the B_4C/C TC is also plotted (hatched area), the mean relative thermopower, e, (where $e = e_A - e_B$) being 287 μVK^{-1} over the entire range. A sensor-specific calibration of the B_4C/C TC appears to be meaningful in view of the width of the reference range. The B_4C/C TC examined showed a constant value of e of 312 μVK^{-1} in the range 1000 -1500 ℃.

After a holding time of 19 h at 1500 ℃, a positive drift of 8 mV, corresponding to ~ 25 K, was found for the B_4C/C TC. During the subsequent stepwise increase in temperature from 1500 to 1800 ℃ (with holding times of 2 h in each case) a value of 291 μVK^{-1} resulted for e. For the remaining time of the experiment, the temperature was kept at 1500 ℃. After 47 h, the drift was +33 K (an error of the first kind). Towards the end of the experiment, the pressure was lowered from 500 to 100 bar. The B_4C/C TC reading simultaneously changed by −62 K (partly an error of the second kind; see also below).

These drifts of the B_4C/C TC reading are plotted in Figure 30. The values up to and including the first 1500 ℃ point are calibration values and are therefore on the x axis. The values at 1600, 1700, and 1800 ℃ are the deviations from the linearly extrapolated calibration curve from 1000 to 1500 ℃.

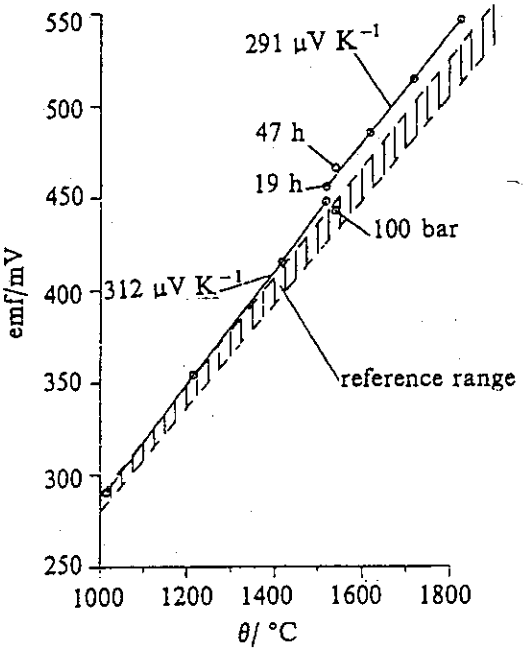


Figure 29 In situ calibration and drift of a B_4C/C thermocouple in an HIP plant (hatched area: reference range according to manufacturer). Pressure: 500 bar.

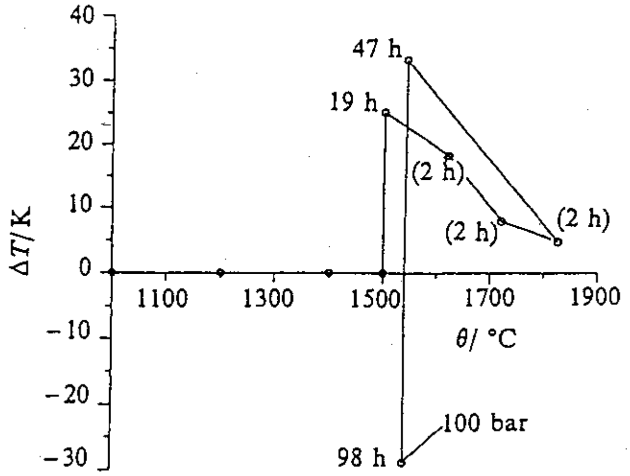


Figure 30 Drift, Δ T, in the reading of a B_4C/C thermocouple in the region of 1500 ℃ as a function of temperature, θ. Operating time are indicated without brackets ; holding times are indicated with brackets. Pressure : 500 bar.

All relevant parameters were constantly checked during the entire test period : the temperature was checked by NT measurements ; the power and pressure of the plant at 1500 ℃ were checked for constancy; the temperatures of the reference junctions were monitored; insulation resistances were checked; and so on.

After removal from the plant, the B_4C/C was checked for homogeneity in a sharp temperature-gradient (0-16 ℃). For comparison purposes, a new B_4C/C TC from the same batch was also examined. While the new TC exhibited a constant relative thermopower ($e = 296\,\mu VK^{-1}$), negative changes in thermopower of up to 10 % were found for the TC used in the test.

A second experiment in the HIP plant with new B_4C/C TC at 1480 ℃ furnished comparable results. Figure 31 shows again the positive drift in the TC reading. The two drift values from the first experiment (Figure 30) after 19 and 47 h at 1500 ℃ are also plotted as single points in Figure 31, as well as value from one other experiment. Considering that the temperatures and previous history of the TCs were not really idential, the points fit into the diagram well.

During these and other experiments, there were also indications of pressure dependencies of the thermopower which, however, are difficult to explain because of changed conditions in the plant owing to varying pressure and which may be only partly attributable to errors of the second kind.

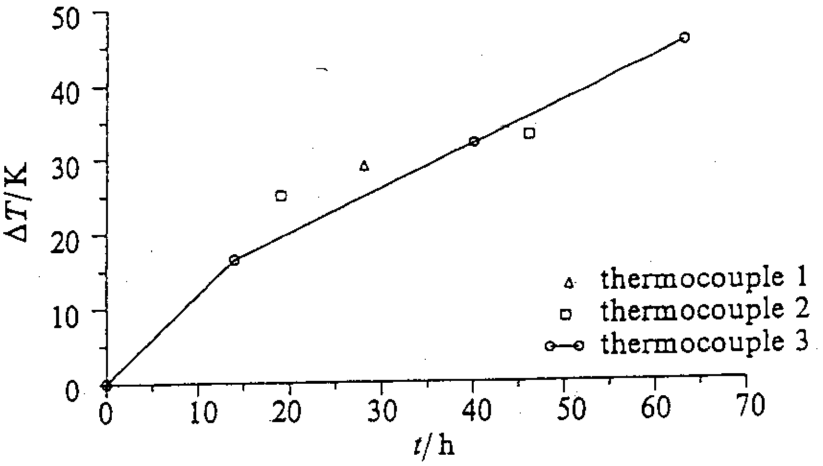


Figure 31 Drift, ΔT, in the readings B_4C/C thermocouples at 1500 ℃, as a function of time, t. Pressure: 500 bar.

The studies of the WRe and B_4C/C TCs have shown that the WRe TC with an appropriate insulator exhibit lower drifts than the B_4C/C TC, in the region of 1500 ℃ ; whereas, in the region of 2000 ℃, inhomogeneities in the WRe TC are generated very fast and the drifts are extremely high,so that the B_4C/C TC has advantages here.

6.1.3.4 Measurement of High Temperatures with Graphite Noise Sensors

A decisive criterion for the service life of sensors in the high-temperature range is choosing the sensor to be compatible with the materials of the sensor environment. As the thermal noise is independent of the material used, the obvious choice in a carbon environment is carbon or graphite (see also Section 5.5).

Measurements with a sensor consisting of a graphite-cord noise resistor and graphite-cord signal condutors in BN insulation beads sheathed with a high purity carbon tube or CFRC-tube (carbon fiber reinforced carbon) showed good results. The sensor with a resistance at 300 K of ca. 1 ohm and ca. 0.5 ohm at 2000 ℃ was tested up to 2100 ℃.

The noise resistance values of sensors of the design described in Section 5.5 are typically in the region of one ohm, although the resistance values of the signal lines are considerably higher (10 to 20 ohm and above). Although this causes unfavourable ratios of useful noise to parasitic noise, nevertheless procedures and measuring instruments for detecting and processing noise signals have now reached such a hig level of development that reliable measurements are possible with a quasi-continuous temperature reading.

Several sensors were tested up to 2200 ℃ and many temperature cycles were performed between room temperature and 2200 ℃ with changes of 100 K/min (Figure 32). The sensors showed very good long-term durability in contrast to, eg, WRe thermocouples.

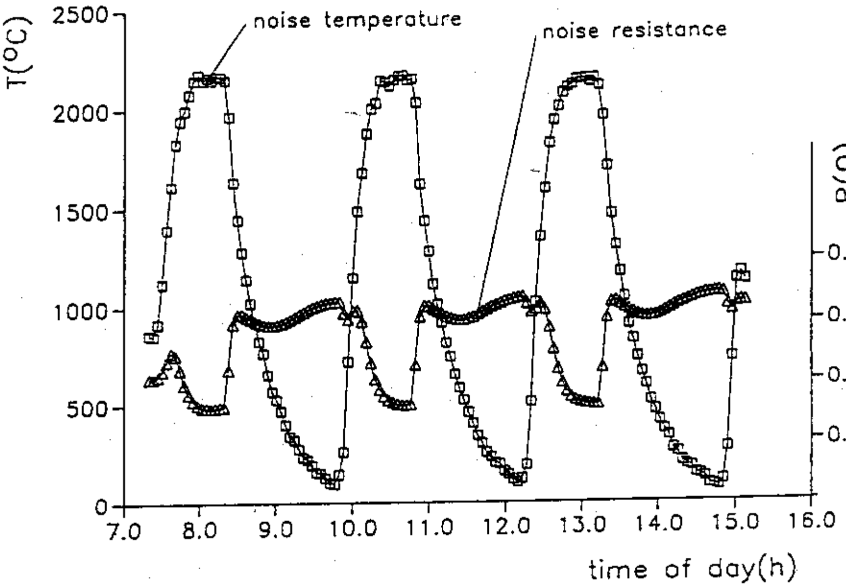


Figure 32 Temperature cycles with an NT-sensor of graphite cord. Also shown (right ordinate) : Time-dependent change of the noise resistance, Rs.

Conclusions

Noise thermometry generally solves the drift problem in the appliation of temperature sensors in the high-temperature range. The use of graphite cord for the noise resistor and signal lines additionally solves the problems of mechanical durability- especially in the case of temperature cycles.

6.2 Applications in Temperature Scale Metrology

Since noise thremometry is a thermodynamic method it has been used for metrological purposes, in particular for determining fixed point temperatures.

With sensing resistances of about 10 kΩ, measurements of ^{4}He at various vapor pressures (near 4 K) were performed with a total uncertainty of only 0.3 mK [34, 35]. In the range 100-500 K uncertainties between 10^{-4} and 10^{-5} were reported using metal film resistors of several kΩ [23, 27, 28, 38]. Between the Sb and the Ag fixed point (630-960 ℃), platinum resistance thermometers with resistance values near 600 Ω at 960℃ were employed with an uncertainty of $2 \cdot 10^{-4} \sim 3 \cdot 10^{-4}$ in the measured temperatures [24, 25, 29].

6.2.1 High Accuracy Noise Thermometry at KFA Jülich

High precision noise temperature measurements at the Zn and Ag fixed points were performed at Jülich in 1988 with an overall uncertainty of $< 3 \cdot 10^{-4}$ [56].

The noise thermometers' precision was then further improved by a number of additional measures. They involved improvements in the shielding and grouding of the whole measurement setup, the linearity of the electronic device, and the signal transmission of sensor and cable, as well as interference detection of external and internal EMI [68].

Extensive tests of the entire measurement arrangement (sensor, transmission line, electronic device with internal reference T_R = 45.15℃) were carried out at the triple point of water in various configurations with respect to power supply, shielding and grounding. An overall uncertainty of ±5 mK at the triple of water (against the internal reference temperature) was obtained from a large number of individual measurements, where the error of each individual measurement remained below ±30 mK.

Figure 33 shows measurement results at the freezing point of Zn. The mean value of 12 measurements is 692.661 K with an uncertainty of ±0.015 K at a confidence level of 0.68. The measurements were performed in different frequency ranges and plateau times of about 8 hours for each single measured value.

The measures described above enabled the uncertainty to be reduced to $\leq 1.10^{-4}$ for a single measurement (corresponding to ≤ ±0.070 K). The mean value of 692.661 K agrees well with the result of Guildner and Edsinger from 1976. This is shown in Figure 34, where the noise thermometer value is added to the drawing of the difference between the International Temperature Scale of 1990 (ITS-90) and the Scale of 1968(IPTS-68) in the range 300 to 800K$^+$

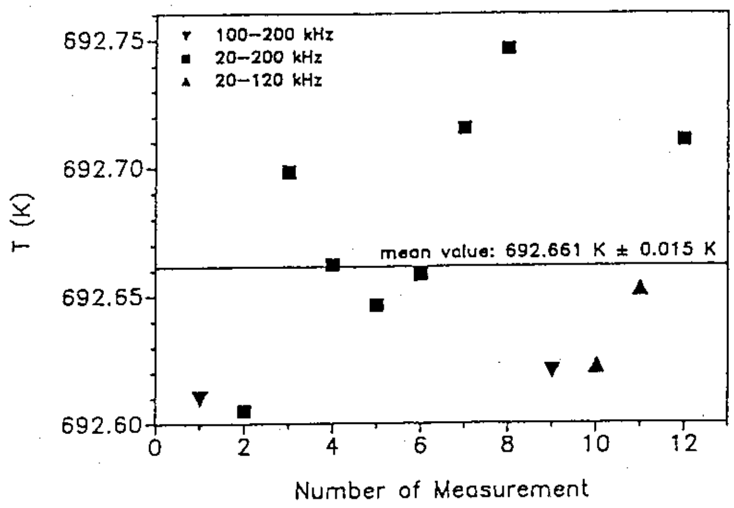


Figure 33 Measurements at the freezing point of Zn (1 σ uncertainty of each measurement point : ≤ ± 70 mK).

Similar measurement at the freezing point of silver are being performed at present .

For the future, the noise thermometer appears very promising even beyond 1000 ℃ because it has the exceptional advantage over other methods that any changes in the sensor are of no significance.

+ " The results of Guildner and Edsinger extended to 730 K, and the data which were selected for fitting by these authors are plotted in Figure 34. The work was later continued by Edsinger and Schooley, who made measurements up to 934 K. They presented results at 505 K, 613 K and 730 K which disagreed with those of Guildner and Edsinger by about 0.01 K, 0.02 K and 0.03 K respectively, but they were unable to account for the discrepancies. In the absence of any other results which could give further guidance, Working Group 4 concluded (with CCT approval) that the differences (T_{90} - T_{68}) should be taken mid-way between the two sets of results. This line is shown in Figure 34. "
(taken from: Working Group 4 des Comite' Consultatif de Thermome' trie, 1989, Second interim report, Document CCT/89-3).

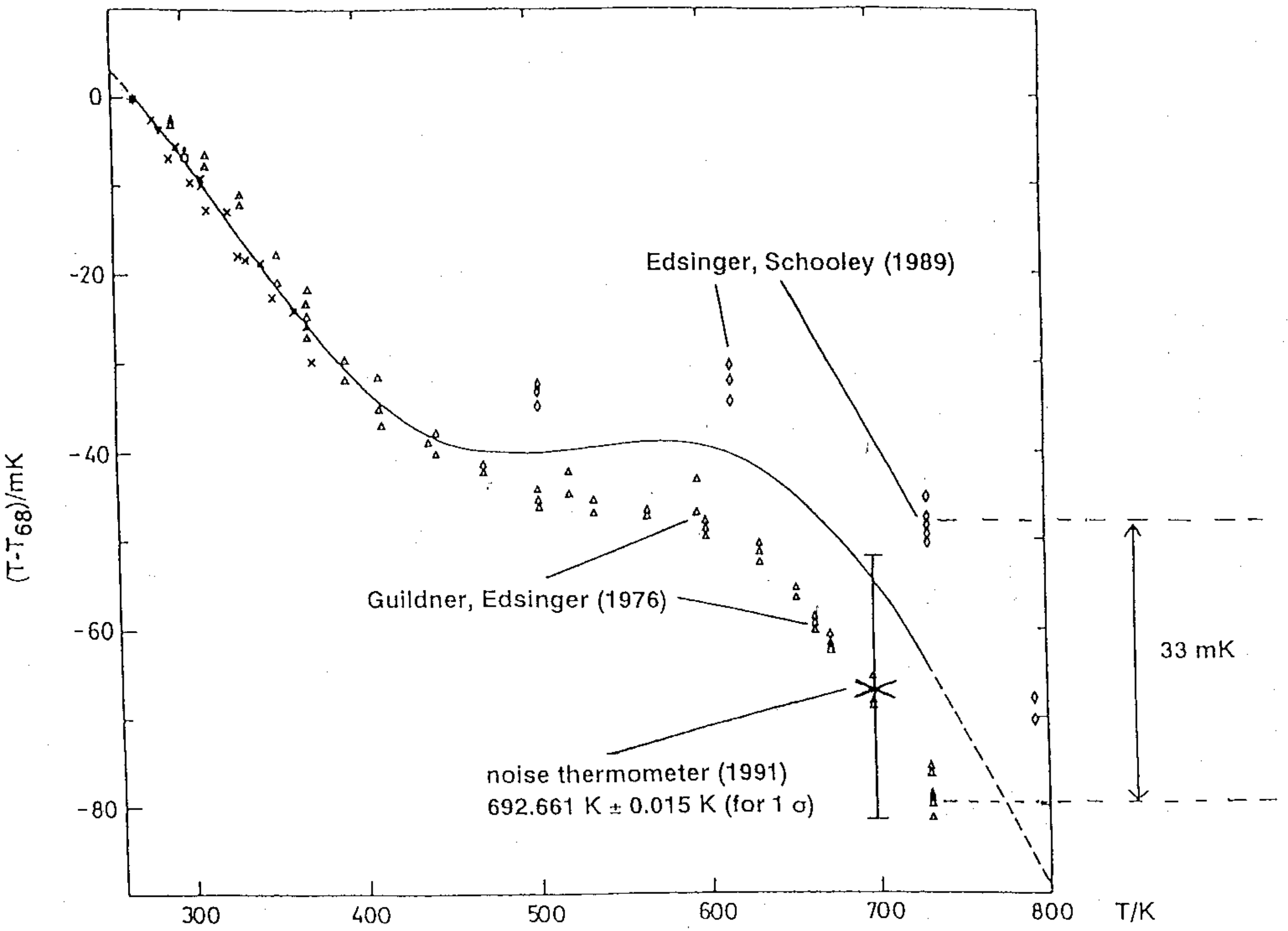


Figure 34 Difference of ITS-90 and IPTS-68 in mK over temperature in K (extended line), and the value measured with the KFA noise thermometer

6. 3 Noise Thermometry at Very Low Temperatures

At very low temperatures, below a few K, the noise power of the amplifier becomes so high in comparison with the noise power of the sensing resistor that reasonable measurements are no longer possible with conventional noise thermometry. The low-noise amplification properties of the Josephson junction can be used to eliminate this problem [64]. Two different Josephson junction devices, a resistive SQUID (superconducting quantum interference device) [64, 65] and a SQUID magnetometer [66, 67], with amplifier temperatures of several millikelvin and less than 0.1 mK, have been employed to measure temperatures from a few millikelvin to 4 K (up to 20 K is possible) with inaccuracies of 1~0.5 % (0.1 % is possible). The resistors are made preferably of silicon-bronze (eg, $Cu_{99}Si_1$) with resistance values of typically 10^{-5} Ω. An overview on absolute noise thermometry at NIST using a resistive SQUID is given in [85].

7 ATTAINABLE ACCURACIES IN THE HIGH-TEMPERATURE RANGE

There often exist illusory ideas about today's attainable accuracies of the thermodynamic temperature in the high temperature range. For instance one can read in scientific publications about measurements at 2000℃ with uncertainties of ±1K.

In the following some statements are cited which were given by three standard laboratories,

Physikalisch - Technische Bundesanstalt,
Berlin,
Germany;
National Physical Laboratory,
Teddington,
United Kingdom;
Nederlands Meetinstituut,
Delft,
the Netherlands;

in a project proposal for the "Measuring and Testing Program" of the European Community, Brussels, in the field of "New Methods of Measurement Leading to Novel Instrumentation ". (KFA Juelich also participates in the project.)

"Measurement of temperatures from 1000 ℃ to 2000 ℃ at present are difficult to perform while traceability in this temperature range depends upon material characteristics which are subject to rapid change at these difficult operational conditions. Temperature is measured in this range with either thermocouples or radiation thermometers. While thermocouples show uncontrolled drift that is difficult to correct for during calibration, radiation thermometry depends upon knowledge of the emissivity of the radiating object. Once an emissivity can not be known to sufficient accuracy one has to rely on thermocouples for temperature measurement. ・・・・

Contact thermometry above 1000 ℃ is realized only with thermocouples. These thermocouples have a short time accuracy of some 0.5 K at 1000 ℃, 5 K at 1500 ℃ and an estimated accuracy of 30 K at 2000 ℃. Partners 1, 3 and 5 (the three standard laboratories) approximate the ITS-90 in this range by noble metal thermocouples and fixed points, with a reproducibility of 0.3 K at 962 ℃, 1.5 K at 1554 ℃ and 3 K at 1772 ℃.

The irreproducibility of these contact thermometers is due to the physical effects that at high temperatures tend to change the material characteristics rather fast. ・・・・

Noise thermometry provides an excellent means of calibration in this temperature range: it is the only system that can acquire an accuracy of better than 0.1 % and unlike pyrometry does not suffer from non-linearity effects as a consequence of the applied comparison technique."

Table 2 shows the accuracies at the Pd and Pt fixed points that could be obtained up to now at Standard Laboratories.

The uncertainties of the melting temperatures of Ni, Co, Fe, Zr and Rh are more or less good estimates.

One must take a factor of about 5 (to 10) of those uncertainties for the usually attainable initial uncertainties in normal laboratories.

Table 2 Accuracies at the measurement of thermodynamic temperatures in the high temperature range

Attained accuracies at some metal melting points, at national standard laboratories (PTB, NBS, NPL, NML.....)

	Melting point [℃]	Uncertainty [K] (max.)	
Pd	1555.0±0.4	1	NML 1978
	1555.4±0.2		NPL 1983
Pt	1767.9±0.3	2.5	NPL 1971
	1769.5±0.6		NML 1974
	1769.0±0.5		PTB 1975
Ni	1455 ±3		
Co	1495 ±3		
Fe	1538 ±3		
Zr	1855 ±8		
Rh	1963 ±5		

8 COMPARISON OF MEASUREMENT 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 an absolute thermometer witch directly gives the thermodynamic 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 advantaegs over thermocouples, if relatively (ie, 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 (advantage 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 eg, 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 point.

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. In Table 3 the noise thermometer and thermocouple are compared.

Table 3 Comparison of noise thermometer (NT) and thermocouple (TC).

Type	Advantages	Disadvantages
NT	Absolute thermometer	Very low signal
	High absolute accuracy	Complex electronic processing
	(applicable as standard)	Sensitive to EMI
	No decalibration, no drift	For high accuracy : long measurement time
	(not impaired by changes of the sensor)	
	Material independent	Expensive
TC	Simple, easy to handle	Secondary thermometer
	Relatively insensitive to EMI	Drift of the emf,decalibration
		(impaired by changes of the sensor)
	Cheap	No high absolute accuracy

The application of combined sensors as depicted in Figure 7 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.

Noise thermometry generally solves the drift problem in the application of temperature sensors in the high-temperature range. The use of graphite cord for the noise resistor and signal lines additionally solves the problems of mechanical durability - especially in the case of temperature cycles.

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ANNEX 1

IMPEDANCE MATCHING OF TRANSMISSION LINES

Fig. A1 represents the typical line arrangement for noise thermometer measurements under plant conditions. The front line section with the measuring sensor consists of a four-wire mineral insulated sheathed measuring line due to the high temperature level. The line section at a lower ambient temperature is designed with two-wire symmetrical plastic insulated lines.

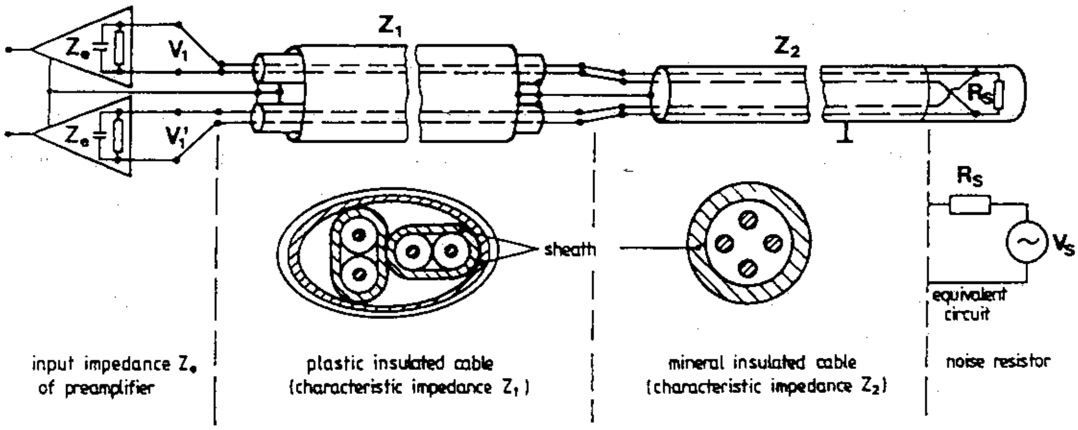


Figure A1 Typical transmission line arrangement
(In Annex 1 the following nomenclature is valid : $R_S \hat{=} R_M$, $V_S \hat{=} U_S$, $V_1 \hat{=} U_1$, $V_1' \hat{=} U_1'$, [52].)

As is generally known, the measurement sensor can be represented in the equivalent circuit diagram as the series circuit of a noiseless resistance with a noise voltage source Us (see Fig. A1).

The transmission features of the line arrangement can thus be described by the transmission functions h(f) or h'(f) of the arrangement, that is to say by the quotient of the voltages U_1 or U'_1 present at the amplifier input and the noise voltage Us :

$$h(f)=\frac{U_1}{U_S} \quad ; \quad h'(f)=\frac{U'_1}{U_S} \qquad \text{(A1)}$$

In noise thermometry, undistorted transmission means that the absolute values of the transmission functions (equation A1) of the arrangement become 1 throughout the entire measuring frequency band. Due to the stochastic nature of the measuring signals the phase angle of the transmission function is of no significance. Nevertheless, it must be ensured that there is no difference in phase shift between the two functions h(f) and h'(f), since this leads to errors when the signals are multiplied. Measurements of the line parameters resulted in good agreement between the individual side circuits with respect to the lines utilized. It is therefore presumed in the following that the difference in phase shift between h(f) and h'(f) is negligibly small.

The transmission behaviour of the line arrangement is determined by the frequency-dependent line parameters as well as by the termination of the lines, that is to say by the input impedance of the amplifier and the value of the measuring resistance. In practice the input impedance of the amplifier is always high enough (R_{in} >1 Megohm, C < 50 pF) to be regarded as an open circuit.

In the case of laboratory measurements with relatively small line lengths the optimum dimensioning of the measuring resistance is of minor significance. However, in the case of plant measurements with large line lengths the particular matching of measuring resistance and lines to each other has proved to be indispensable.

Therefore the dimensioning of the measuring resistance must be possible with sufficient precision when noise thermometer is operationally employed, not least because in many cases of application the measuring sensors cannot be replaced at will. For this reason a computer programme has been developed with the aid of which the optimum measuring resistance for a particular noise thermometer arrangement can be determined.

The mathematical description of the lines' transmission behaviour is carried out with aid of the line equations (equ. A2). The concomitant reference arrow system is given in Fig. A2.

$$\begin{pmatrix} U_1 \\ I_1 \end{pmatrix} = \begin{bmatrix} ch(\gamma l) & Z_W sh(\gamma l) \\ sh(\gamma l)/Z_W & ch(\gamma l) \end{bmatrix} \cdot \begin{pmatrix} U_2 \\ I_2 \end{pmatrix} \qquad \text{(A2)}$$

$$Z_W = \sqrt{\frac{R'+j\omega L'}{G'+j\omega C'}} \quad \text{characteristic impedance} \qquad \text{(A3)}$$

$$\gamma = \sqrt{(R'+j\omega L')(G'+j\omega C')} \quad \text{propagation constant} \qquad \text{(A4)}$$

l   line length

R', L', G', C' : resistance, inductance, leakage conductance, capacitance each per unit length.

A prerequisite for the applicability of equation (A2) is the homogeneity and linearity of the cables involved. These requirements, as will be shown in the following, can, at least piecewise, be fulfilled in all cases of application.

Figure A2 Reference arrow system with respect to the line equations (A2)

Non-linearities in the line route of noise thermometer arrangements can only occur when combined TC/NT sensors are employed, with which it becomes necessary in part to use magnetic wire materials. Due to the low signal amplitudes of the noise spectrum it can however be presumed that hysteresis distortions are negligible. Furthermore, magnetic wire materials can be avoided in the plastic insulated line section in all cases interesting in practice by the use of non-magnetic extension cables.

Inhomogeneities can only occur in the mineral insulated line section in temperature gradients. They are caused by increasing the series resistances of the line wires, by decreasing the insulation resistances, by changes in the line capacitances and in the case of magnetic wire materials by changes in magnetic behavior in the range of the respective Curie temperature.

The temperature coefficients of the wire materials used are sufficiently small so that the series resistance of the lines can be regarded as constant in sections even at steep temperature gradients. The same is valid for the insulation resistances.

In order to estimate the changes in line capacitance in temperature gradients the relative dielectric constant ε_r of several mineral cables was measured as a function of the temperature. The results with MgO as the insulating material are depicted in Fig. A3 ; Al_2O_3 displays the same qualitative behaviour.

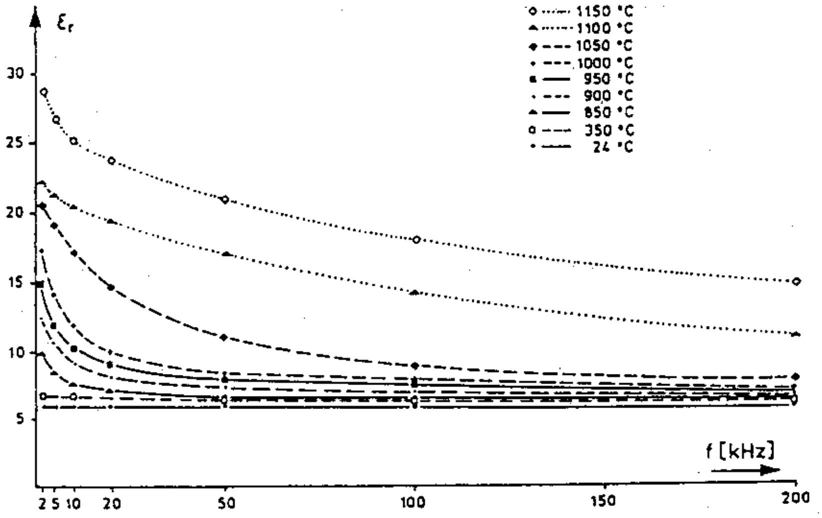


Figure A3 Typical frequency characteristic of the relative dielectric constant ε_r of MgO in commercial cables

As can be seen from Fig. A3, the changes in ε_r in the interesting frequency band (about 20-200 kHz) are so slight up to approx. 1000 ℃ that the capacitance of the lines can also be regarded as constant in sections. In the range above 1000 ℃ where the changes in ε_r become larger, G' is decisive in the equations (A3) and (A4) so that even large changes in ε_r only have a relatively weak effect.

Possible effects of magnetic line wires on the transmission of noise signals have still to be clarified. It was assumed for the calculations that the homogeneity is not influenced by μ_r (i.e. sectionwise homogeneous lines). More detailed investigations into this complex of questions are being undertaken at present.

From all the above, it follows that the transmission line can be represented as a connection in series of homogeneous, linear line sections whose transmission behaviour can in each case be determined with the aid of equation (A2).

If one combines the individual line sections then a linear, passive, time-invariant twoport results as can be seen in Fig. A4, the twoport parameters of which A_{11}, A_{12}, A_{21} and A_{22} can be calculated from the connection in series of the individual line sections. In the case of the measuring resistance the factor 2 results from the reduction of the two-channel arrangement to an equivalent one channel arrangement.

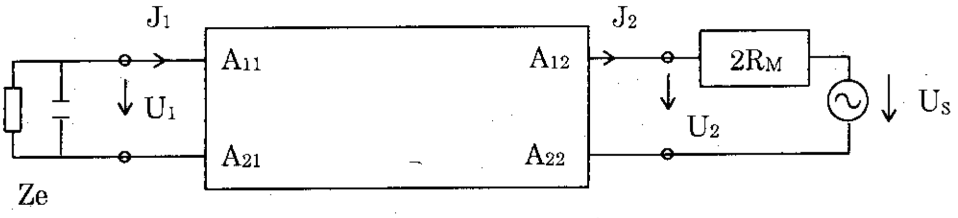


Figure A4 Equivalent twoport of a series of individual line sections

According to Fig. A4 the transmission function h(f) of the arrangement can be calculated to give:

$$h(f) = \frac{K}{2R_M A_{21} + A_{22}} \tag{A5}$$

K is a correction factor which takes the influence of the amplifier input resistance into consideration (K=1 for $Z_e \rightarrow \infty$). For finitely large input impedances the correction factor can be calculated to give :

$$K = \frac{1}{1 + \frac{1}{Z_e} \frac{2R_M A_{11} + A_{12}}{2R_M A_{21} + A_{22}}} \tag{A6}$$

In practice, the correction factor is approximately 1 over the whole interesting frequency range. In the calculations carried out the input impedance was taken into consideration as a connection in parallel of 1 Megohm with 30 pF.

The transmission behaviour of the line arrangement with the measuring resistance as signal generator and the amplifier input impedance as line termination is completely described by euqation (A5). Cross-talk from one side circuit into the adjacent circuit is not taken into consideration. (Cross-talk from parasitic noise sources, such as the series resistances of the line wires or the insulation resistances, can lead to genuine measuring errors since these signals, as correlated signals, would not be eliminated by a subsequent correlation technique.)

The two line circuits are individually shielded in the plastic insulated line section (see Fig. A1). Moreover, the position of the line wires is selected in such a way that, together with the shielding, cross-talk in this line section is in practice negligible. In the mineral insulated line section the four line wires lie together in only one shielding. However, estimates have indicated that with sufficiently high insulation resistance, cross-talk is also negligible in this section. The sensors' behaviour at very high temperatures, and thus rapidly decreasing insulation resistances, is discussed in Section 4.4 and Annex 2.

As can be seen from equation (A2) to (A4) the transmission behaviour of the lines is completely described by the four line parameters: resistance R', inductance L', leakage conductance G', and capacitance C', each per unit length. These four parameters can be determined at room temperature by a simple measurement. Generally they are frequency - dependent and due to the material parameters also temperature-dependent. If the temperature dependence of the materials used is known then the line parameters at elevated temperatures can be sufficiently well approximated, starting from the values measured at room temperature. The parameters measured in this way contain all influences decisive in the transmission behaviour of the lines, such as the skin effect, the proximity effect etc.

The absolute square value of the transmission function is decisive for the transmission behaviour of the line arrangement with respect to noise spectra.

The relative error which occurs by the distortion of the measuring spectrum through the transmission lines thus results as :

$$F = \frac{\int_{fu}^{fo} \left| h^2(f) \right| df}{fo - fu} - 1 \tag{A7}$$

with h(f) from equation A5.

Fig. A5 shows the curves of $|h^2(f)|$ for an ideal 50 ohms line of 100 m. Fig. A6 shows the same line's frequency range interesting for noise thermometer measurements in an extended form. It can be seen, as was to be expected, that an ideal matching results for $R_M=Z_W/2$ over the entire frequency range. If the line losses are taken into consideration particularly the line wires' series resistances, then the curves represented in Fig. A6 are displaced downwards in the upper frequency range as a function of the value of the series resistances (see Fig.A7).

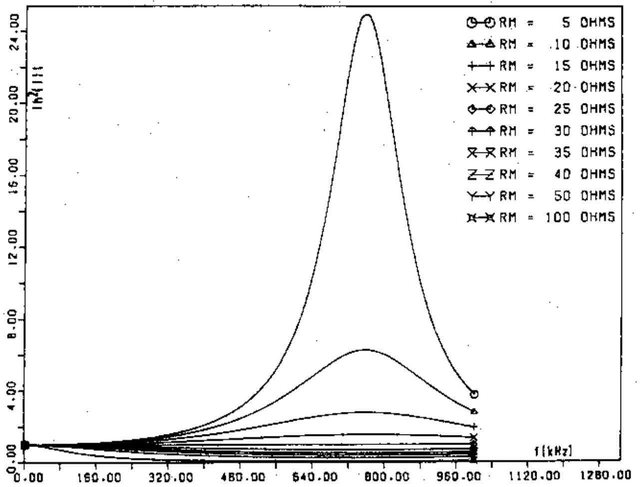


Figure A5 Transmission behaviour of an ideal cable (Zw = 50 ohms, 1 = 100m)

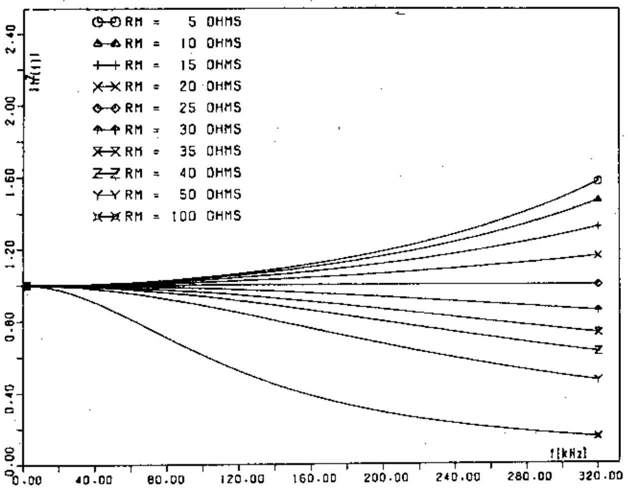


Figure A6 Transmission behaviour of an ideal cable (Zw = 50 ohms, 1 = 100m)

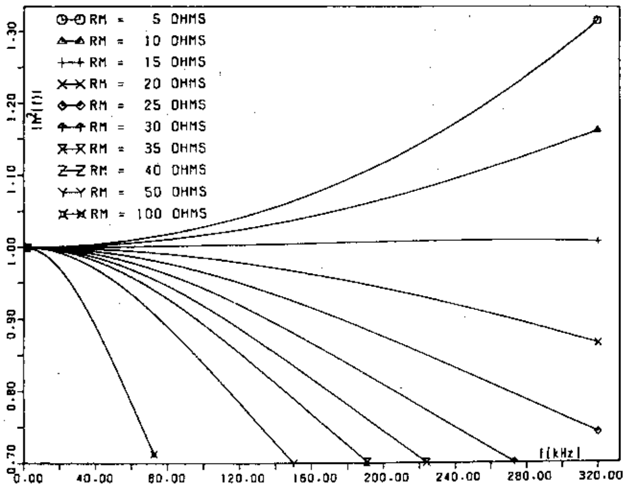


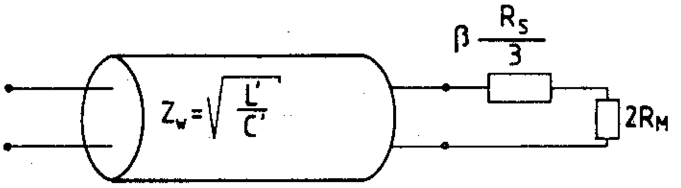
Figure A7 Transmission behaviour of a cable with series resistance per unit length of 0.5ohms/m (Zw = 50 ohms, 1 = 100)

In order to obtain an estimate of the optimum dimensioning of the measuring resistance, taking line losses into consideration, the line wires' resistance in the equivalent diagram can be considered with a part of its value as a series resistance to R_M. As is well known the series resistance of a short ($l < \lambda / 32$) open-ended line has to be taken into account in the equivalent circuit diagram with 1 / 3 of its value due to the linear current distribution. With larger lines (up to $l < \lambda / 8$) the series resistance has to be multiplied by an additional frequency-dependent correction factor (see Fig. A8), because in that case the current distribution is no longer linear [69]. The line can then be regarded as loss- free and can be denoted by the characteristic impedance $Z_w = \sqrt{L'/C'}$. It must be noted that Z_w is now also frequency-dependent on the basis of the frequency dependence of L' due to the skin effect etc. The corresponding equivalent diagram is given in Fig.A8.

The value of the measuring resistance results from Fig. A8:

$$R_M = \left(Z_W - \beta R_L / 3\right) / 2 \tag{A8}$$

As can be seen from equation (A8) optimum matching in the whole frequency range is not possible with dissipative lines due to the frequency dependence of both Z_w and R_L. Parameter calculations have indicated that it is most favourable for calculating R_M according to equation (A8) if the line parameters are taken at the upper frequency limit used for measurements.



$\beta = 1 + \frac{1}{10} \cdot \left(\frac{2\pi\ell}{\lambda}\right)^2$ for $l < \lambda / 8$

$\beta \approx 1$ for $l < \lambda / 32$

ℓ	cable length
λ	wave length
R_L	resistance of line wires
R_M	measuring resistance

Fig. A8 Equivalent diagram for estimating R_M

In order to test the accuracy of the programme, noise thermometer measurements were carried out according to Fig. A9.

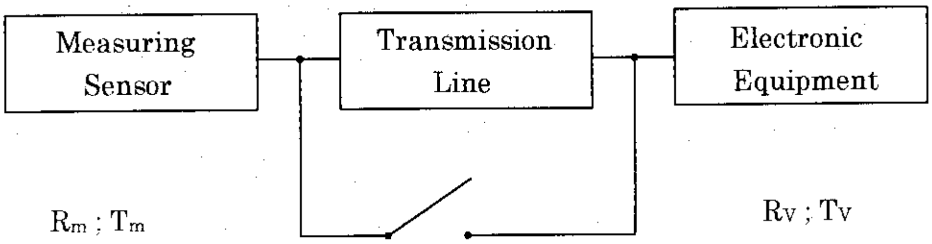


Fig. A9 Block diagram for experimentally determining the transmission behavior of lines by means of the noise thermometer
(Nomenclature : $R_M \hat{=} R_S$, $T_M \hat{=} T_S$, $R_V \hat{=} R_R$, $T_V \hat{=} T_R$)

A measuring resistance (at a constant temperature) was applied to the electronic measuring equipment first via a very short line and then via a long transmission line. The resulting differences in the measured values thus correspond to the influence of the transmission line.

Table I Measured and calculated transmission errors of a mismatched (over - matched) copper cable of 90 m length

Bandwidth	Transmission Error		$\frac{F_r - F_m}{F_m}$ %
	measured	calculated	
kHz	F_m %	F_r %	
30-300	-24.8	-22.1	-10.9
100-200	-22.2	-19.1	-13.9
20-200	-13.9	-12.4	-10.8
15-150	- 8.6	- 7.7	-11.7
10-100	- 4.1	- 3.6	-12.2
10- 80	- 2.6	- 2.4	- 7.7
10- 60	- 1.46	- 1.44	- 1.4
10- 35	- 0.46	- 0.54	17.4
5- 25	- 0.27	- 0.24	-11.1

Table I presents the results of measurements for a symmetrical plastic insulated copper line with a characteristic impedance of approx. 170 ohms and a length of 90 meters, together with the corresponding calculated values. The relative deviation between measurement and calculation is given in column 4. With good matching the transmission errors of a copper line are relatively small, even at a length of 90 meters. In order to obtain significant values for comparison with the calculation, a considerably over-matched value was selected here with

R_M = 130 ohms, in which case large transmission errors occur (negative error). Good matching can be obtained with the above-mentioned line at a R_M of approx. 80 ohms. As can be seen from Table I, the transmission behaviour of the line is well represented by the computer programme.

Table II Measured and calculated transmission errors of a mismatched (under- matched) transmission line arrangement for a reactor experiment

Bandwidth	Transmission Error		$\frac{F_r - F_m}{F_m}$ %
	measured	calculated	
kHz	F_m %	F_r^* %	
30-300	1.274	1.69	31.87
20-200	0.726	0.78	7.44
15-150	0.42	0.45	6.67
10- 60	0.00	0.06	--

The results of out-of-pile measurements for a line arrangement of a nuclear reactor experiment are depicted in Table II. The line arrangement consisted of a mineral insulated sheathed measuring line of 4 meters (Cu wires, external diameter 2 mm, impedance approx. 65 ohms at 200kHz) and a plastic insulated symmetrical line of 20 meters (impedance 90 ohms). The value of the measuring resistance amounted to 27 ohms. In order to obtain a sufficiently high useful signal, the sensor tip was heated during the measurement to a temperature of 650 ℃ also later to be extended in the reactor experiment. In order to also enable a comparison between measured and calculated values here, a higher impedance of the plastic cable of Z_w = 90 ohms was chosen than would have corresponded to an optimum matching. A positive error thus results. (On the other hand, the matching of R_M to the mineral insulated sheathed measuring line is relatively good.) It can thus be seen that also with this measuring arrangement calculation and experiment are in good agreement. By reducing the upper band limit to 60 kHz, transmission errors can be avoided in spite of considerable mismatching of the plastic cable.

ANNEX 2

MEASUREMENT SENSORS AND CABLES AT HIGH TEMPERATURES

As in the case of thermocouples, mineral insulated sheathed measuring lines are also used for noise thermometers in the hot zone when measuring high temperatures. Considerable line resistances are present at lengths up to 10 m and above. These can be of the same order of magnitude as the measuring resistance. These resistances of the measuring lines, which in part are at non-determinable temperatures, are in series with the measuring resistance so that their noise is additively superimposed on the useful noise.

The problem has however been solved in principle by the application of 4 lines to the measuring resistor - a sheathed 4-wire cable is employed for this purpose - and by the cross correlation of their noise voltages.

Since the insulating resistance of mineral insulated lines decreases greatly with rising temperature, a signal loss occurs on the one hand and on the other coupling of parasitic signals, both in the case of noise thermometers and thermocouples, at high temperatures and long hot zones (insulation error).

The signal loss results from shunts due to low insulation resistances between the lines as well as between the lines and the cladding. Then again parasitic noise results from the insulation resistances (R_{is}) if these are no longer very much greater than the measuring resistance (R_M). This is to say, the noise signal comes from connection in parallel $R_M // R_{is}$.

Moreover the cross correlation for the line resistance is canceled in part by low insulation resistances, since from these a parasitic, correlated signal is also imposed on the useful signal.

As long as the measuring resistance as well as the insulation resistances and line resistances discussed here are at the same temperature, this whole coupled network can be regarded as noise resistance. When measuring the resistance (in a four-wire circuit) this total noise resistance is also determined. In this case no error is made in measuring the noise temperature (this presumes white spectrum in the measuring frequency band). However - as is always the case in practice - if the cable, or parts of it, are at different temperatures from R_M (and thus parts of the insulation and line resistance), then a measuring error results which depends on the value of the insulation resistance in comparison to R_M, on the value of the line resistances in the corresponding temperature range as well as on the temperature distribution.

The coupling of R_M, R_{is} and the line resistance R_L is not easy in the case of a noise sensor, as the simplified diagram (Fig. A10) shows. Furthermore, the temperature distribution and the value of R_{is} and R_L are in general not known. (The inductances and capacitances of the cable play a minor role in considering the insulation error. They are therefore not plotted in Fig. A10 for reasons of clarity.)

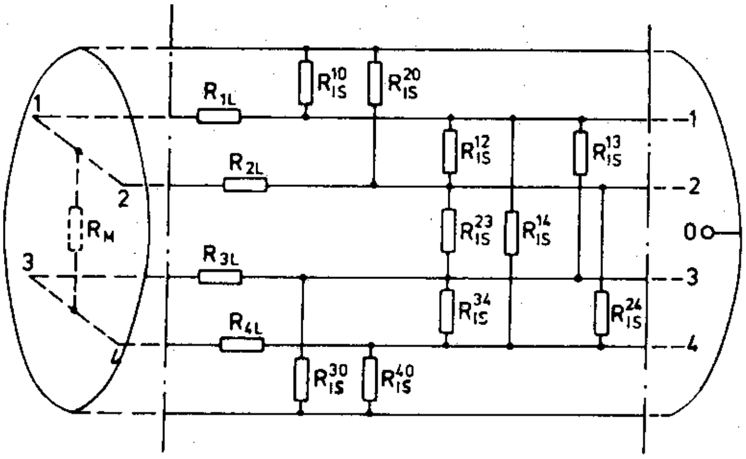


Figure A10 Simplified equivalent circuit diagram of a differential cable section

Due to the complex interconnection of signal gain and loss, the influence of the insulation resistance in the case of combined TC-NT's was investigated experimentally in two temperature configurations which are typical in practice. That is to say with the measuring sensor tip in the temperature maximum or beyond the temperature maximum in a colder zone.

The position of the TC-NT's in the temperature field is shown schematically in Fig.A11. Some measuring lines were coiled spirally in the hot zone in order to enable the investigation of large lengths at high temperature (approx. 2 m in the zone of maximum temperature). Four-wire, MgO insulated, sheathed NiCr/Ni measuring lines with an external diameter of 6 mm were used.

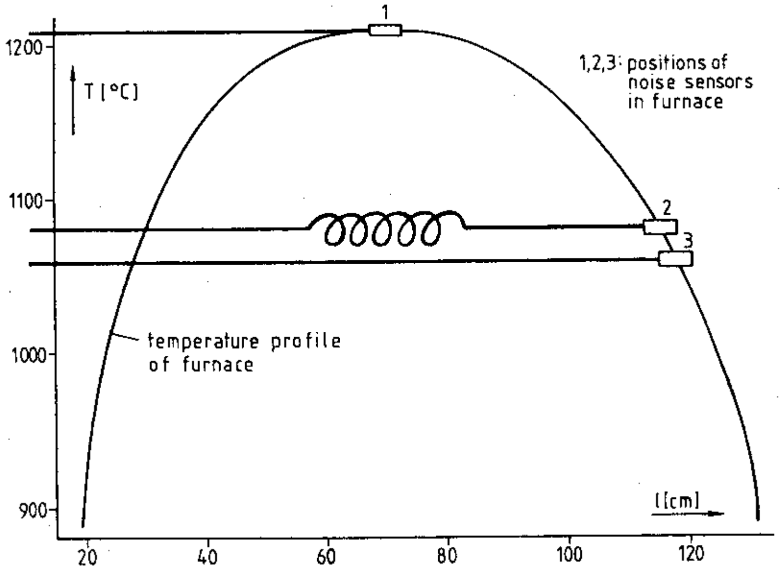


Figure A11 Temperature profile of furnace and position of TC-NT sensors and mineral insulated cables

Fig. A12 shows the results of measuring sensors whose tips were beyond the temperature maximum in a 100 to 150 K lower temperature range. The deviation of the measured noise temperature from the real temperature in K is plotted against the ratio of the insulation resistance R_{is} to the measuring resistance R_M. The temperature of the hottest zone is given in brackets for each measuring point. The three measurement curves indicate that with the unfavourable positioning of the measuring sensors in the temperature field described above (tip of the measuring sensor beyond the zone of maximum temperature), a ratio of the insulation resistance to the measuring resistance (R_{is} / R_M) of 10 to 15 is sufficient to keep the relative insulation error under 0.5 % for noise temperature measurements.

If the measuring sensor tip is positioned in the zone of maximum temperature then the noise temperature error were under 0.5 % down to a ratio $R_{is} / R_M = 6$. These results show that even at relatively low insulation resistances, i.e. at very high temperatures or in long hot zones, the noise thermometer provides reliable values.

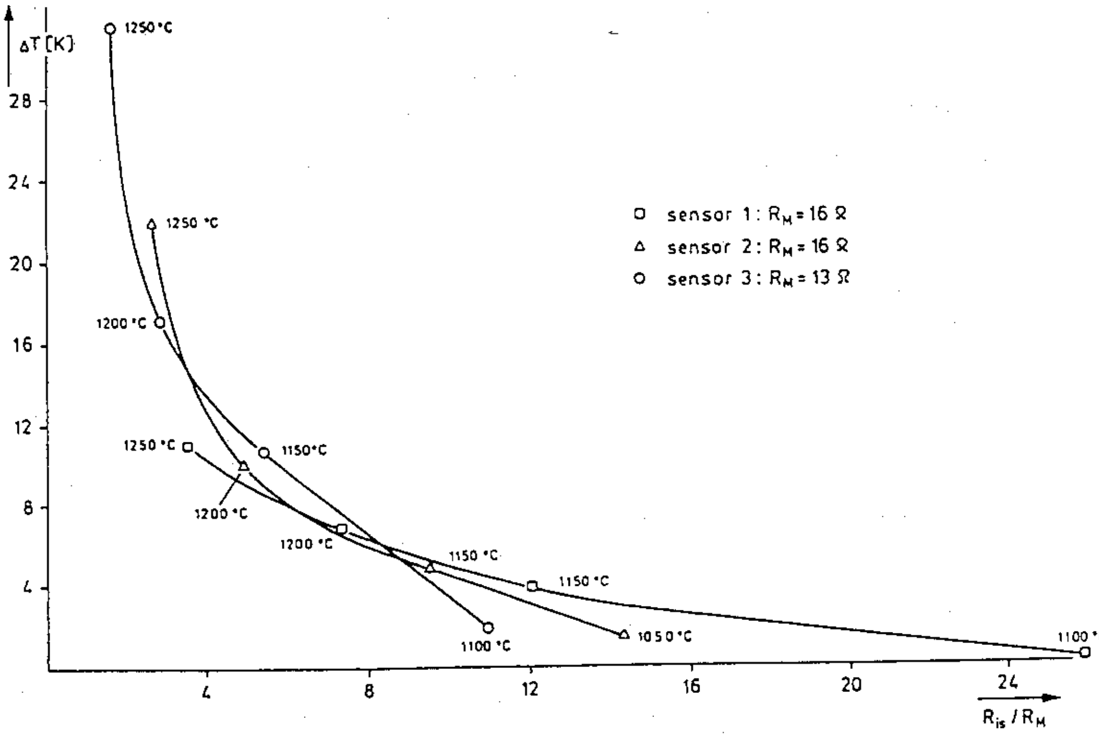


Figure A12 Deviation of noise temperature for 3 sensors in position 2 and 3 of Figure A11

It is of course in principle advantageous to use sheathed measuring lines which still display good insulation resistances even at high temperatures. Long-term investigations have therefore been carried out on a great number of industrially produced mineral insulated sheathed measuring lines of different dimensions and materials from various manufacturers.

Fig. A13 represents the results of insulation resistance measurements on four-wire NiCr/Ni, MgO-insulated sheathed measuring lines (all four wires together against the sheath).

The insulation resistances of almost all sheathed measuring lines could be found in the hatched area in Fig. A13. However, a particular batch from a certain manufacturer displayed insulation values which were better by one order of magnitude (dashed curve in Fig. A13). The reason for this could not be determined. Nevertheless, this example shows that it is technically possible to manufacture sheathed measuring lines with sufficiently good insulation resistances for utilization in large-scale industrial plants (long hot zones).

If the insulation resistance of sheathed measuring lines is no longer sufficient at high temperatures, then hard sintered, rigid ceramics (eg, Al_2O_3, BeO) are used for insulation. A disadvantage, however, is in this case the different expansion coefficients of the insulating ceramic and line wires which can lead to destruction of the measuring sensor.

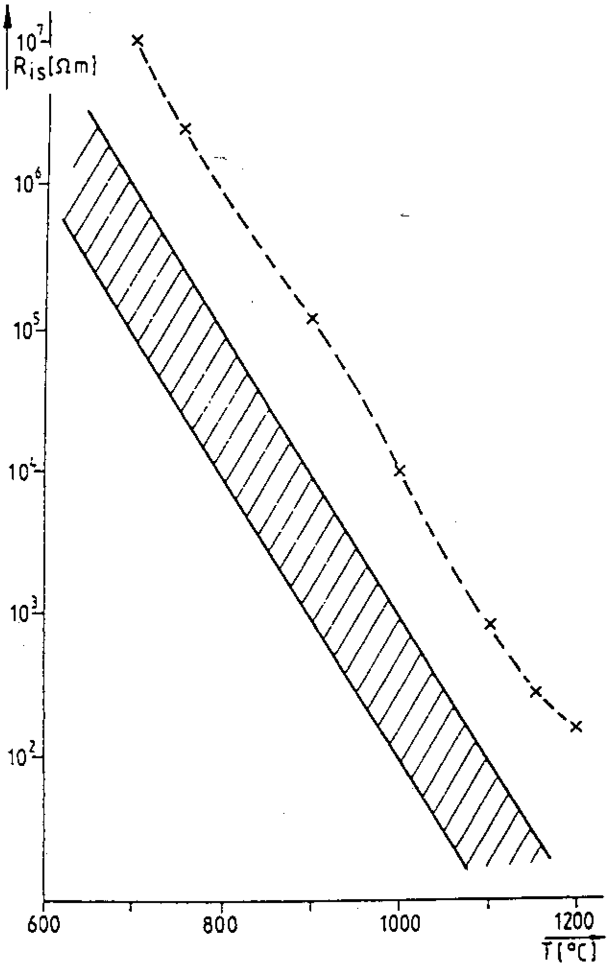


Figure A13 Insulation resistance of commercial, 4-wire MgO-insulated sheathed cables