IAEA-TC-389/6-6

# HIGH TEMPERATURE MEASUREMENT by NOISE THERMOMETRY

Marc C. Decreton

Department of Technology and Energy
CEN/SCK Nuclear Research Center
B–2400 MOL (Belgium)

IAEA International Working Group on Gas Cooled Reactors
Specialists' Meeting on Gas Cooled Reactor Core
and High Temperature Instrumentation
June 14–17, 1982, Windermere, England

## ABSTRACT

*Noise thermometry has received a lot of attention for measurements of temperatures in the high range around 1000 - 2000 °K. For these measurements, laboratory type experiments have been mostly performed. These have shown the interest of the technique when long term stability, high precision and insensibility to external conditions are concerned.*
*This is particularly true for measurements in nuclear reactors where important drifts due to irradiation effects are experienced with other measurement techniques as thermocouple for instance.*

*Industrial noise thermometer experiments have not been performed extensively up to now. The subject of the present study is the development of a 1800 °K noise thermometer for nuclear applications.*

*The measurement method is based on a generalized noise power approach. The rms noise voltage ($V_s$) and noise current ($I_s$) are successively measured on the resistive sensor. The same quantities are also measured on a dummy short circuited probe ($V_d$ and $I_d$). The temperature is then deduced from these measured values by the following formula :*

$$cT_s = (V_s^2 - V_d^2) \left( \frac{V_s}{I_s} - \frac{V_d}{I_d} \right)^{-1}$$

*where c is a constant and $T_s$ the absolute temperature of the sensor.*

*This approach has the particular advantage of greatly reducing the sensibility to environmental perturbations on the leads and to the influence of amplifier noise sources. It also eliminates the necessity of resistance measurement and keeps the electronic circuits as simple as possible.*

*The method is used in the present study for measurements up to 1800 °K by using a niobium sheated probe containing the resistive and the short-circuited sensors. Platinum wires are used for the resistance coil and the leads, the insulation being made of alumina.*

*Out of pile tests have been performed in a typical industrial environment using a regulated oven. Calibration measurements have also been made using the freezing points of gold and nickel.*

*The first results have shown that the global accuracy lays around 0.3 % in the temperature range 300 - 1800 °K, using an integration time of 10 s.*

*Taking into account the fact that no periodic recalibration is necessary, this method presents a very interesting alternative to conventional high temperature thermocouple techniques.*


./.

## 1. INTRODUCTION

*Measuring high temperatures with great accuracy and stability over long periods of time is of primary concern in many aspects of engineering activities, such as in the nuclear industry or in metallurgical process techniques, for instance. Usual methods as thermocouple or resistance measurements present non-negligible limitations when used above 1000 °C over long periods.*
*For thermocouples, for instance, diffusion of impurities from the environment or the ceramic insulation, exchange of alloying components, preferential evaporation, recrystallization or change of phase, reduce in a sensible way their long term accuracy [ 1 ]. In a radiation field, this effect is further enhanced by material transmutation. Fig. 1 shows an example of the observed drift of a W-Re thermocouple placed in a neutron flux [ 2 ]. A deviation ratio of 0.8 is already found for a fluence of* $2.10^{21}$ *neutrons/cm*$^2$*. On the other hand, resistance thermometers, using platinum for instance, are quite unreliable above 800 °C [ 3 ].*

*For a few years now, attention has been directed to new kinds of temperature measurements [ 4 ]. Among these, the noise thermometry is one of the most promising. It basically uses the thermal agitation of the electrons in a conductor as an indicator of its temperature. This thermal agitation appears as a white noise signal at the ends of a resistor. The measurement of this signal makes it possible to derive the temperature of the sensor. The method has the major advantage of being independent of all environmental conditions and of the properties of the material itself, used for the probe. Moreover, it indicates the absolute temperature and the physical law linking the temperature and the measured signal is linear [ 14 ].*

## 2. NOISE SIGNAL

*Electrical noise due to thermal agitation has been first described by Nyquist [ 5 ] and Johnson [ 6 ]. An unloaded passive network always presents at its ends a voltage, fluctuating statistically around zero. The mean square of this voltage is given by*

$$\overline{e_n^2} = \{4\ k\ T\ R\}\ \{\frac{hf}{kT}\ (e^{\frac{hf}{kT}} - 1)^{-1}\}\quad [V^2/Hz] \qquad (1)$$

*where h and k are the Planck's and Boltzmann's constants repectively, T the absolute temperature, f the frequency and R the resistance. For temperature above 100 °K and frequencies below 1 GHz, Eqn. (1) can be accurately approximated by*

$$\overline{e_n^2} = 4\ k\ T\ R \qquad [V^2/Hz] \qquad (2)$$

./.

B mW

*Eqn. (2) represents a white noise signal independent of the frequency. In a practical measurement, a given bandwidth Δf is imposed and the true rms voltage is then given by*

$$\sqrt{\overline{v_n^2}} = \sqrt{4\,k\,T\,R\,\Delta f} \qquad [V] \qquad (3)$$

*When the current is measured instead of the voltage, the equivalent model of the noise signal gives*

$$\sqrt{\overline{i_n^2}} = \sqrt{4\,k\,T\,\Delta f\,\frac{1}{R}} \qquad [A] \qquad (4)$$

*By multiplying Eqns. (3) and (4), one obtains a noise power*

$$P_n = 4\,k\,\Delta f\,T \qquad [W] \qquad (5)$$

*independent of the resistance value and presenting thus a totally linear relationship between signal and absolute temperature.*

## 3. NOISE MEASUREMENT TECHNIQUES

*Noise thermometry is based on the measurement of one of the previously defined quantities : noise voltage, noise current or noise power. It offers in all cases an absolute temperature scale independent of the way the sensor is built. But, due to the very low levels of the signals to be measured, typically a few tenths of microvolt or some nanoamperes, noise thermometry has been usually limited in its applications, to laboratory calibration measurements. Actually, the technique used without precaution suffers from a variety of drawbacks that can in some cases put aside the benefits of it. This comes primarily from the influence of the amplifier internal noise, its stability in time, the parasitic noise appearing in the cables and the great complexity of the measurement procedures.*

*Direct reading methods have thus been eliminated to the advantage of comparative methods, first introduced in 1949 [ 7 ] and recently extended for high precision high temperature laboratory calibrations [ 8 ] . In this technique, also called ratio method, the noise voltage from the sensor is compared to the noise voltage of a reference resistor placed at a known temperature.*
*After carefully adjusting the reference resistor and obtaining two equal noise levels, the temperature is deduced from the resistance ratio. The technique can achieve high precision but is somewhat difficult to use in an industrial environment.*
*Each measurement needs careful adjustments and accurate knowledge of the sensor resistance. Besides this, the set-up is very sensitive to external pick-up noise in the connecting cables and to the influence of capacitive effects.*

./.

*A modification of the ratio method has been proposed [8], [9], [10] in order to decrease the influence of external pick-up noises and amplifier internal noise. The approach is called the correlation method. The connections between the sensor and the measuring apparatus are doubled, as well as the preamplifier section. The signals coming from each separate path are correlated. This eliminates any unwanted noise coming from the cables or the amplifier. Measurements up to 1000 K have been reported in a nuclear reactor environment [10]. The extension of this technique to higher temperatures leads, however to great difficulties due to the necessity to measure the two resistor values. At high temperatures, the leaks through the insulation can become an important source of uncertainties [11].*

*In order to avoid this resistance measurement, the noise power method has been proposed [12], [13]. Measuring the noise power instead of the voltage has actually two main advantages, particularly important when high temperature industrial measurements are kept in mind. The measurements do not necessitate any adjustment and can be totally automated. The measured value is linearly proportional with the temperature. Secondly, there is no need for any resistance measurement, avoiding the many sources of error from insulation leakage. However, compared to the correlation approach, the power method is much more sensitive to external pick-up noises and thermal noises generated in the connecting cables, as well as to the internal noise generated in the amplifier. A "quiet" environment is actually not easily practicable in real industrial situations.*

## 4. NOISE THERMOMETRY - PRESENT METHOD

*The method proposed in this paper as well as in [16], [17] basically relies on the power approach. Having, however, as particular guidelines, to design a practical method for industrial applications, the emphasis is set here on reducing the overall complexity of the electronics and the measurement procedure. At the same time, it was aimed to decrease as much as possible, the sensibility of the measurement accuracy with respect to extraneous interferences, that are always present in a technical environment. As a matter of fact, Eqn. (5) used by Borkowski and Blalock [12] is only valid if external pick-up noise along the cables or thermal noise localized in the leads can be neglected. These conditions are, however, difficult to achieve in practice and these parameters are then likely to be the chief sources of errors. In order to avoid these problems, a supplementary measurement is proposed. The noise voltage and current of a dummy, short-circuited, probe are measured along with the resistor probe measurements. In order to be representative, this short-circuited probe must be placed as close as possible to the effective resistor and must present an exactly similar cable link to the preamplifier. At the limit, a four-leads cable is to be used where two leads are short-circuited at the end and the other two connected to the resistor. This arrangement will permit to extract from the measured values the influence of cable and preamplifier noise as long as they are stationary. These two unwanted noises can be represented by equivalent resistances* $R_c$ *and* $R_a$ *at the temperatures* $T_c$ *and* $T_a$ *respectively.*

./.

*The rms measured noises can then be written as*

$$V_s = G_v \sqrt{4\ k\ \Delta f\ (R_s\ T_s + R_c\ T_c + R_a\ T_a)} \qquad [V] \qquad (6)$$

$$V_d = G_v \sqrt{4\ k\ \Delta f\ (R_s\ T_c + R_a\ T_a)} \qquad [V] \qquad (7)$$

$$I_s = \frac{G_i \sqrt{4\ k\ \Delta f\ (R_s\ T_s + R_c\ T_c + R_a\ T_a)}}{(R_s + R_c + R_{in})} \qquad [A] \qquad (8)$$

$$I_d = \frac{G_i \sqrt{4\ k\ \Delta f\ (R_c\ T_c + R_a\ T_a)}}{(R_c + R_{in})} \qquad [A] \qquad (9)$$

*where $R_{in}$ is the input resistance of the preamplifier. It is to be noted that Eqns. (6) to (9) can only be written if the amplifier has the same characteristics for both the voltage and current measurements.*

*The unwanted contributions are eliminated by computing the following expressions*

$$A = \frac{V_s}{I_s} - \frac{V_d}{I_d} = \frac{G_v}{G_i} R_s \qquad [\Omega] \qquad (10)$$

$$B = \frac{V_s^2 - V_d^2}{A} = 4\ k\ G_v\ G_i\ \Delta f\ T_s = KT_s \qquad [W] \qquad (11)$$

*This last quantity is proportional to the sensor temperature $T_s$, offering thus a linear absolute temperature scale.*

*The schematic diagram of the measurement set up is given on Fig. 2. Two switches are used to select one of the four measurements to be made : $V_s$, $I_s$, $V_d$, $I_d$. A specially developed electronics performs the very low noise amplification, and a band pass filtering. The output is then measured via a commercially available rms digital voltmeter with a selective integration time. A microprocessor can be added to control and automate the measurement procedure. A direct display in degrees can then be achieved.*
*Two elements of this set up are determinant for a proper design : the sensor and the low noise amplifier. These two components are discussed in the next sections.*

## 5. THERMOMETER PROBE

*The thermometer probe can in principle consist of any electrical resistance, the choice of material being very large since the variations of ohmic value with temperature and time is of no importance. The order of magnitude of the resistance value is, however, determined by the optimum functioning of the measuring electronics. Furthermore, very small values will reduce, in a too great extend, the noise level, as high values, on the other hand, introduce a high frequency attenuation in combination with the cable capacitance and therefore a difficult definition of the available bandwidth. A resistance of 10 to a few hundred ohms is usually selected.*

*The particular difficulty is then to achieve such a value in a very small volume in order to measure a temperature as localized as possible. The probe must also be able to withstand continuous high temperatures and maintain sufficient electrical insulation Moreover, in order to reduce as much as possible any pick-up noise, attention must also be focused on a proper electromagnetic shielding.*

*Two constructions have been tested. They are represented on Figs. 3 and 4. The first one uses a 6-bore alumina tube as insulation piece and a thin platinum wire wound inside it. The second design presents a rhenium wire coil around an alumina matrix with an helical groove, protected by an outer alumina tube. In both cases, the sheath is made of niobium and contains both the resistive sensor and the dummy short circuit. Alumina has been chosen for its good temperature properties and its availability in different shapes. The use of beryllia was not considered due to the related toxicity problems. The choice of niobium for the sheath is the result of a compromise between cost, shielding properties, mechanical strength and weldability. Platinum is very costly and has a poor mechanical strength. Molybdenum and other refractory metals are difficult to weld. Niobium, on the contrary, when welded by a pulsed laser beam under protective atmosphere, presents mechanical resistance and machinability comparable with stainless steel. Moreover, it offers a better thermal and electrical conductibility. Platinum and rhenium have been chosen for the winding wires due to their availability in very small diameter. It is to be noted that the rhenium construction has the advantage of requiring a much smaller length of wire for the same resistive value.*
*The two sensors have a 3 mm diameter and a 30 mm length. They present a room temperature resistive value of 43 and 45 ohm respectively.*
*They are extented by 50 to 100 cm of niobium-sheathed alumina-insulated four-wire cable to the point where stainless steel sheathed cable can be used. The leads of the resistive sensor and the short circuit follow thus the same path and are contained in the same sheath enclosure.*

## 6. LOW NOISE AMPLIFIER

*The basic lay-out of the preamplifier circuit is given on Fig. 5. A great simplification is introduced by using the same amplifier as a voltage-sensitive or a current-sensitive instrument. Only the feedback circuit is adapted to each case by switching S2. The voltage and current measurement corresponds to the position v and i respectively. This design guarantees an almost identical inherent noise level for both configurations. It reduces also to a great extent the number of components and the overall complexity and cost.*

*By using a carefully designed first stage preamplifier with 5 parallel mounted F E T 2N 6550 transistors, the total equivalent noise resistance, for both measurement options, is around 8 Ω. The following gains are achieved :*

$$G_v : 9750 \quad , \quad G_i \cong 2.22\ 10^6$$

*(This last gain is actually the transfer function of the current amplifier expressed in ohms).*

*The preamplifier is followed by a combined amplifier and a filtering circuit made of four operational amplifiers. The choice of the bandwidth depends on a certain number of constraints :*

- *A large bandwidth produces a high output signal level (Eqn. 5).*
- *The frequency response is degraded at high frequencies by the cable and the amplifier input capacity. The possibility of using 20 to 30 m long cables is to be considered. Therefore a choice of around 40 kHz for the upper band frequency is reasonable.*
- *The lower limit of the bandwidth is chosen at 15 kHz. This eliminates the 1/f noise generated in the electronic circuit and the interference noise coming from the power mains.*
- *The slopes are of no real importance for an exact definition of Eqn. 5. Δf appears as a constant factor that can be experimentally determined together with the amplifier gain. Care must be taken, however, to assure a great stability of both the gain and the frequency response.*

*The output signal is detected via a true RMS digital voltmeter and the value is, afterwards, integrated over a defined period. A SOLARTRON 7075 digital voltmeter is used for this purpose.*

*The position sequence of the two switches, the corresponding measurements and the computation of the quantity B (Eqn. (11) ), are automated by a microprocessor controlled system allowing the direct display of the temperature after each measurement.*

./.

## 7. MEASUREMENT RESULTS

A laboratory test has been set up in order to evaluate the performance of the designed noise thermometer.

A type I probe was first introduced in a [illegible]ated oven covering a temperature range from ambiant to 850°C. A Chromel-Alumel thermocouple fixed on the noise thermometer probe was used as a reference. For each temperature, the four quantities $V_s$, $I_s$, $V_d$ and $I_d$ were registred using an integration time of 10 s. For a better definition, the mean value of 10 successive readings was calculated. Using Eqn. (11), the corresponding B values were computed. Fig. 6 shows the measured quantity as a function of the absolute temperature measured with the reference thermocouple. The measurements were made in a typical industrial environment in the proximity of several large electrical motors and switching devices. No detectable influence were registred during start up or switching procedures. In Fig. 6, the measured points are compared with the straight line obtained by linear regression. The observed errors around this line are of the order of 0.25 %. This error must be compared with the errors due to the reference Chromel Alumel thermocouple, the errors of the voltmeter and the inherent statistical error given in percent by

$$\varepsilon = 100 \frac{1}{2 \quad \Delta f \, t} \qquad [\%] \qquad (12)$$

where t is the integration time. Eqn. 12 gives in the present case arount 0.1 %. This error is given for one measurement of voltage or current. In the case of Eqn. (11), the obtained error is slightly higher and approach 0.15 %. The observed errors are thus well in the foreseen boundaries. By measuring only one value after an integration time of 10 s, the observed error is around 0.5 %. A series of calibration tests have also been conducted using some standard freezing point temperatures as water, tin, cadmium and zinc. Fig. 6 shows the measured results, for which the observed error with respect to the straight line are all around 0.2 %.

Tests have also been carried out at higher temperature following the same procedure in an oven regulated by 2 platinum /10 % rhenium thermocouples. Measurements have been extended from 1000 to 1800 K with steps of 50 K.

Figs. 7 and 8 show the results obtained with the two types of sensors. The black dots are the measured values of the quantity B (Eqn. 11) as functions of the temperatures recorded by the reference thermocouples. One clearly sees that they all fall along a straight line passing through zero (linear regression line). The observed errors with respect to this line have mean values around 0.38 and 0.30 % respectively. The rhenium coil sensor appears thus to present a somewhat better performance.

Calibration measurements have also been made with molten metal baths. The gold and nickel freezing points were chosen as reference points. The open dots on Figs. 7 and 8 show the obtained results. Using the previously defined regression line, one finds errors of 0.32 and 0.28 % respectively for the two types of sensors.

./.

## 8. CONCLUSION

*A particular approach for a noise thermometer has been proposed. By measuring the noise voltage and noise current, the noise power can be computed. This eliminates the need for measuring the resistance value. The use of the same amplifier for both measurements with different feedback reduces in a great extent the complexity and the cost of the electronic circuit. At the same time, the noise contribution of the amplifier for the voltage and current measurements is the same and an important simplification can therefore be obtained in the mathematical treatment. In order to decrease as much as possible the influence of electromagnetic pick-up and thermal noise in the cables, and internal noise in the preamplifier, a comparison measurement is made with a dummy sensor, short-circuited at its end. The quantity derived from both configurations is shown to be linear with the absolute temperature. An error of around 0.30 % is observed with an integration time of 10 s. This error is due to the cumulative influence of the statistical error inherent to the method, the RMS voltmeter error, and the inaccuracy of the reference temperature. No detectable influence of electromagnetic interferences has been found, even for tests made in a typical industrial environment.*

*Work is presently in progress in order to increase the accuracy and the mechanical reliability of the sensors.*

## 9. REFERENCES

[1] Burns, G.W., Hurst, W.S., in Temperature Measurements, Institute of Physics Conference Series, vol. 26, Eds. Billing, B.F., Quinn, T.J., London, pp. 144-161 (1975).

[2] HEBEL W., MOONS F., POTT G., Commission of the European Communities, Report n° EUR-5648-e (1977).

[3] JOHNSTON J.S., in Temperature Measurements, Ed. B.F. Billing and T.J. Quinn, Inst. of Physics, Conference Series, vol.26, (London and Bristol, Inst. of Physics), 80-90 (1975)

[4] Tasman, H.A., Richter, J., High Temp.-High Pressures 11, 87 (1979).

[5] NYQUIST H., Phys. Rev. 32, 110-113 (1928).

[6] JOHNSON J.B., Phys. Rev. 32, 97-100 (1928).

[7] GARRISON J.B., LAWSON A.W., Rev. Sci. Instrum., 20, 785-794 (1949).

[8] Crovini, L., High Temp.-High Pressures, 12, 253 (1980)

[9] Storm, L., Z. Angew. Phys., 28, 331 (1970).

[10] Brixy, H., Heckert, R., Overhoff, T., Symposium on Nuclear Power Plant Control and Instrumentation, Vienna, 1973, pp. 637-648.

[11] Crovini, L., Actis, A., in Temperature Measurement, Institute of Physics Conference Series, vol. 26, Eds. Billing, B.F., Quin, T.J., London, 1975, pp. 398-408.

[12] Borkowski, C.J., Blalock, T.V., Rev. Sci., Instrum., 45, 151 (1974).

[13] Shepard, R.L., Borkowski, C.J., East, J.K., Fox, R.J., Morton, J.L., Colloquium on High Temperature In-Pile thermometry, Petten, 1974, report EUR-5395, pp. 737-774.

[14] Blalock, T.V., Shepard R.L., A decade of progress in high temperature Johnson noise thermometry, 6th Symposium on Temperature, Washington, March 15-18, 1982.

[15] Decreton M., Binard, L., Delrez C., Hebel, W., Schubert, W., High Temp.-High Pressures, 12, 395 (1980).

[16] Decreton, M.C., High Temperature noise thermometry for industrial applications, 6th Symposium on Temperature, Washington, March 15-18, 1982.

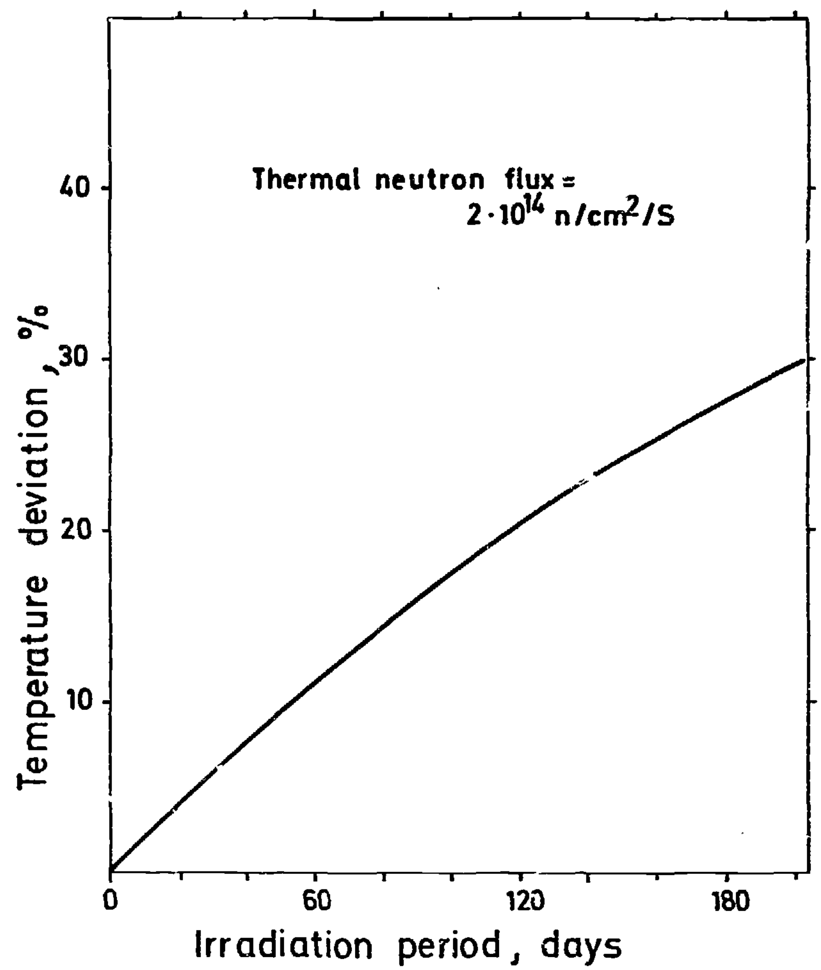


Fig. 1 Temperature deviation of a W-5% Re / W-26% Re thermocouple in a neutron flux as a function of time.

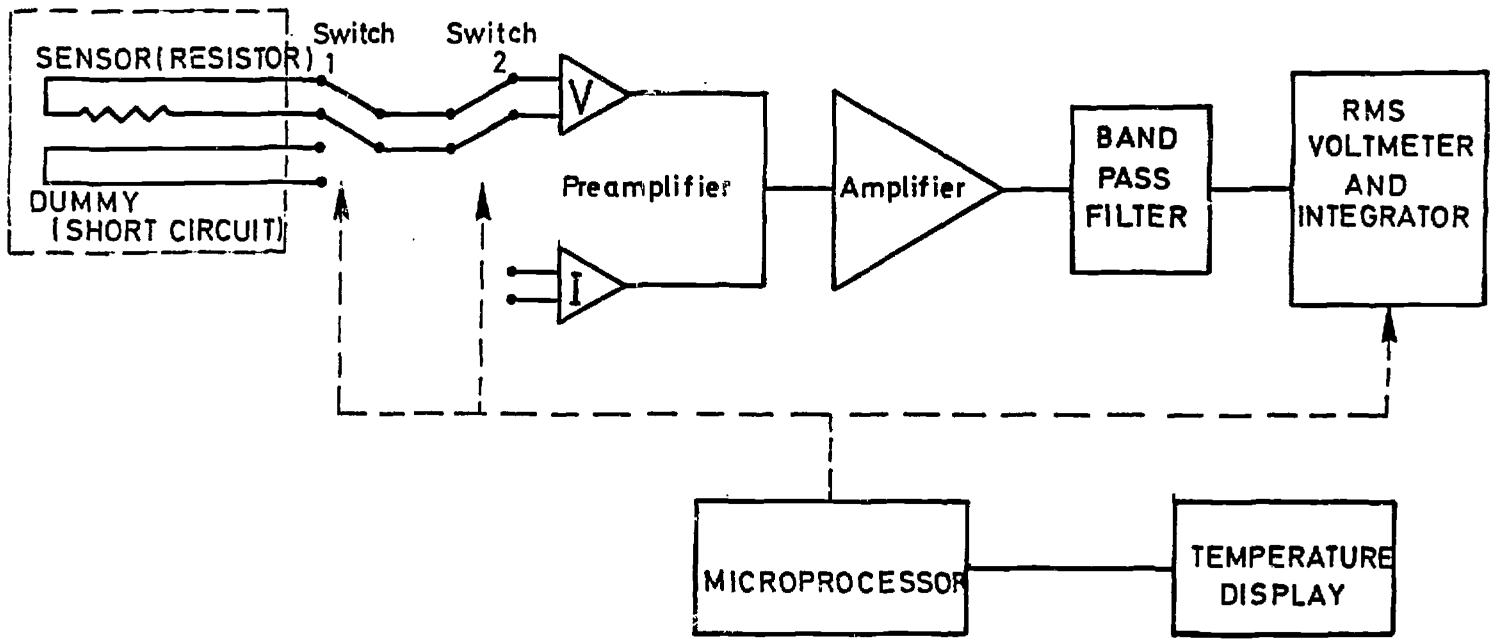


Fig. 2 Measurement Scheme.

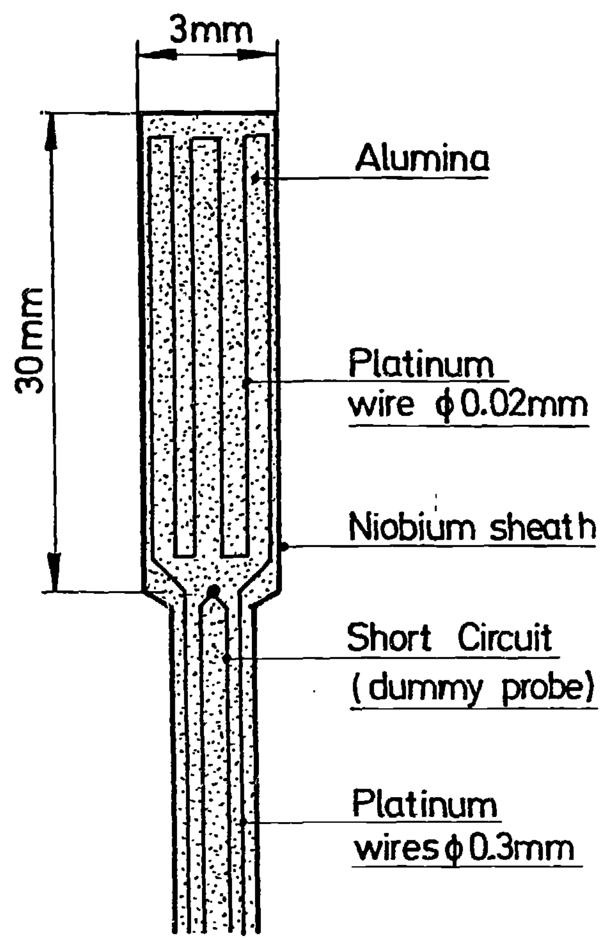


Fig. 3 Sensor construction
(type I, Platinum wire).

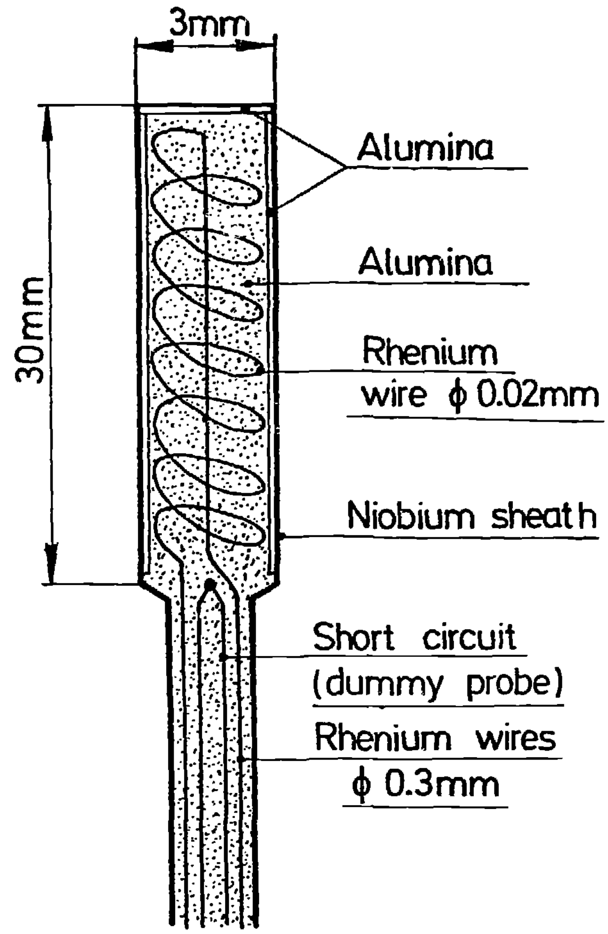


Fig. 4 Sensor construction
(type II Rhenium wire).

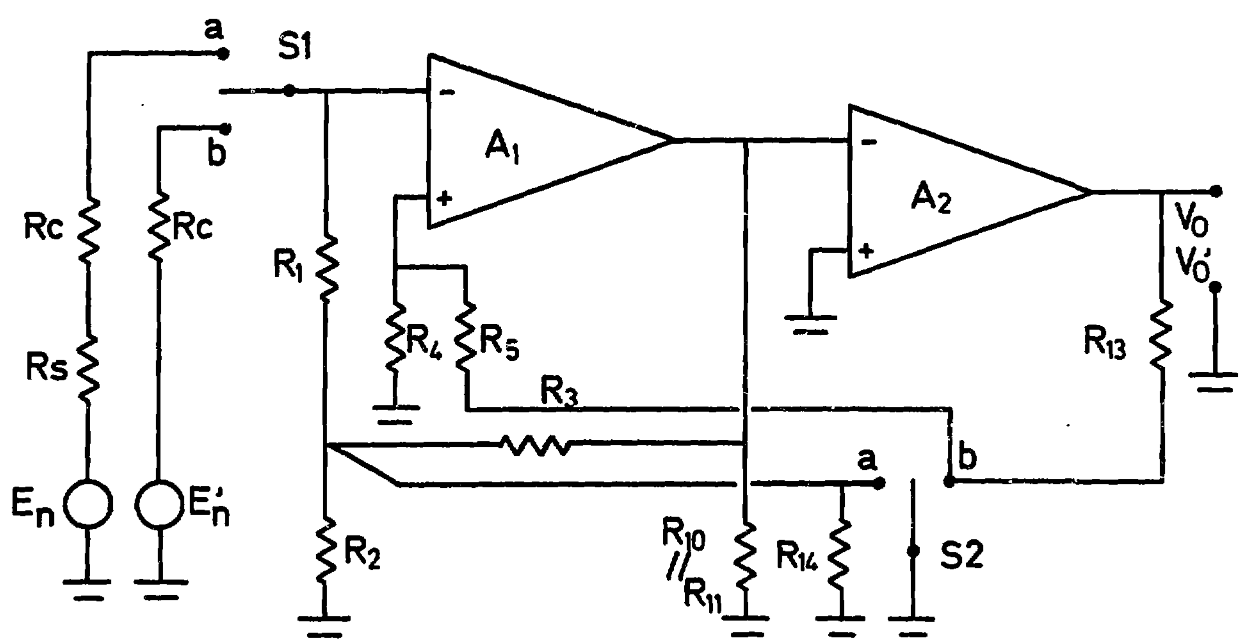


Fig. 5 Preamplifier schematic lay-out.

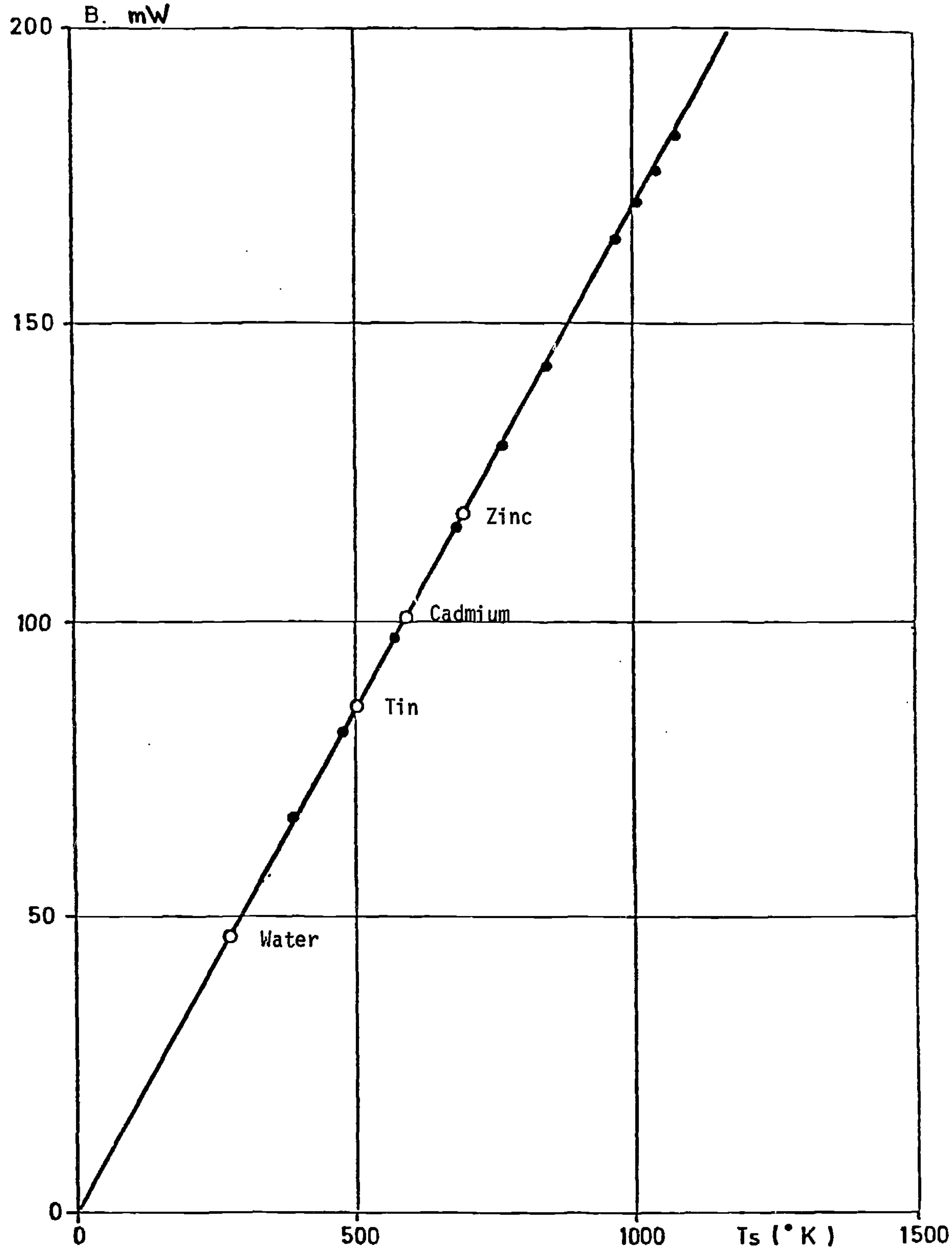


Fig. 6 Measurement Results for type I sensor (low temperature range).

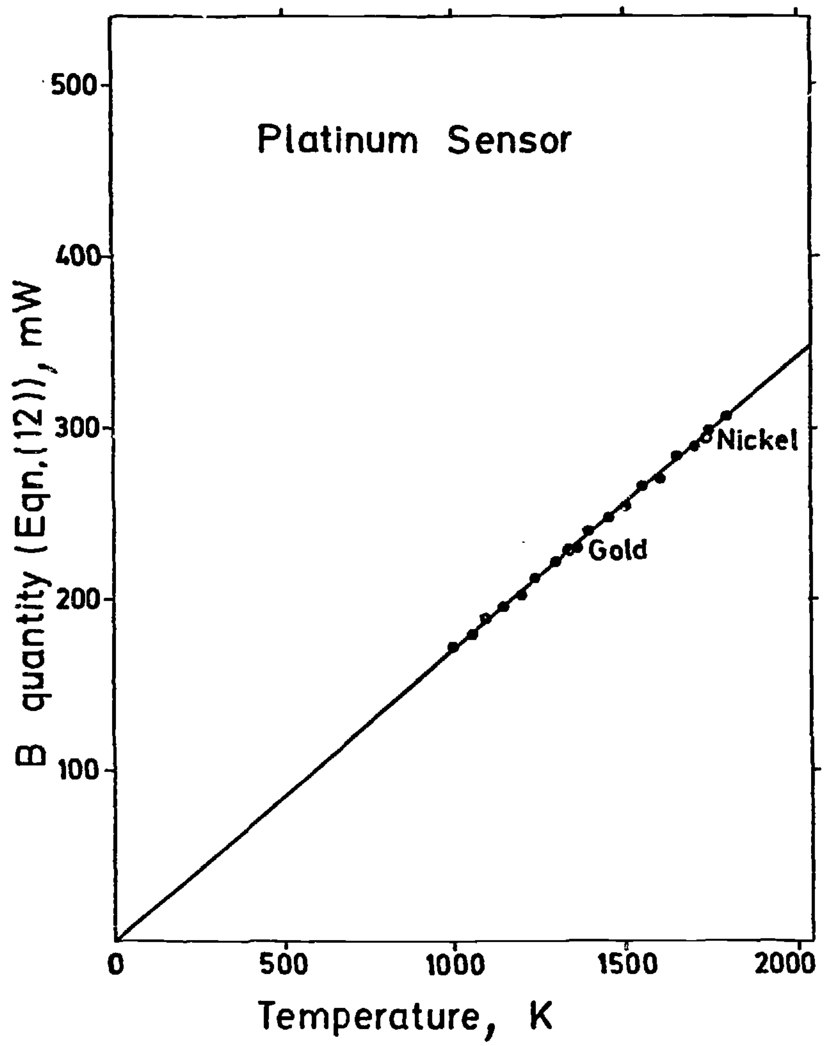


Fig. 7 Measurement Results for type I sensor.

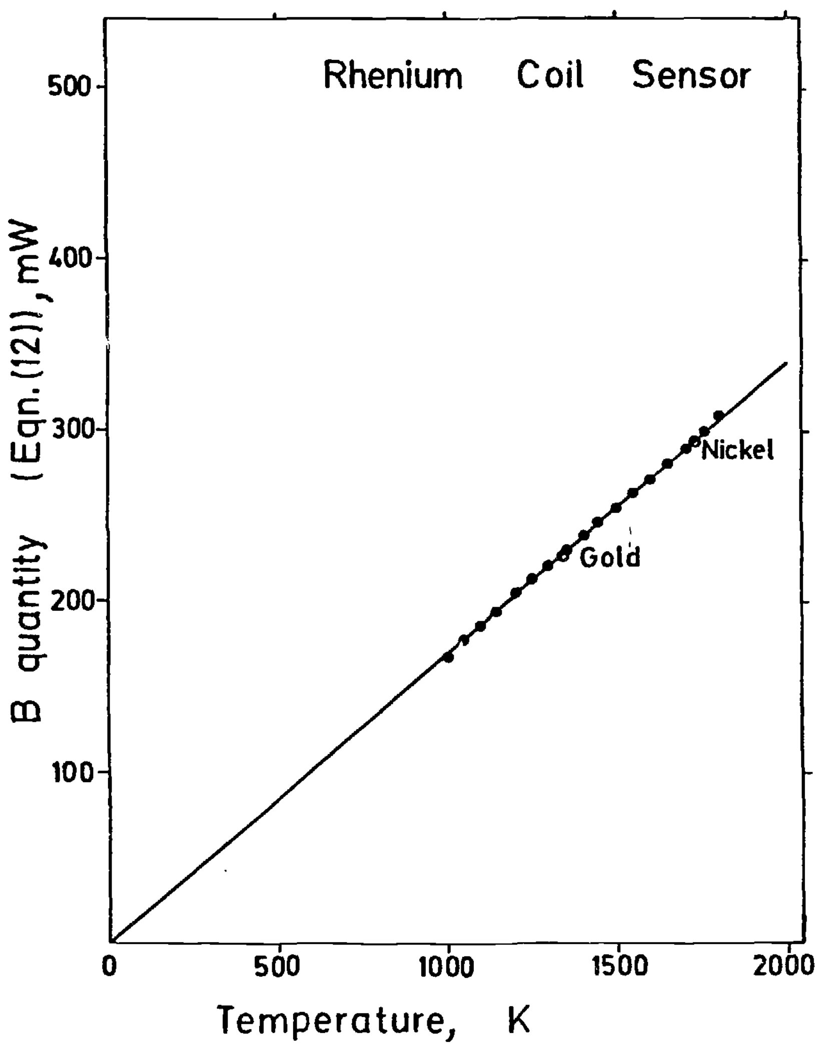


Fig. 8 Measurement Results for type II sensor.