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TIME TO SUBSCRIBE TO THE
ISOTECH JOURNAL OF THERMOMETRY FOR 1992

We continue to be gratified by the acceptance of our Journal of Thermometry.

In Volume 1, No. 1 (1990) we wrote:

"It is with a genuine sense of trepidation that we undertake to found and publish a new Journal. How shall we justify this rash act to ourselves and to our colleagues in temperature metrology?"

Your subscriptions have given us reason to believe that we were indeed justified, and your occasional and too-infrequent comments indicate that the Isotech Journal is read, shared, and becomes a part of your technical library. We know also of cases where it has been the Basis of teaching and training material.

Thus, after two years, four issues, we happily announce our third year of publication.

This year, individual subscription notices will be sent by mail to all previous subscribers. Those of our friends who subscribed late in 1991, telling us that they had 'not received notice' (although notice appeared on Page 47 of Vol. 1 No. 2) will not lose the opportunity. There will be a price increase for 1992, forced by increased cost of printing, postage and exchange, to $25 or £15 for the two issues of 1990 if you send us a check, or $35 (£20) if you require that we invoice you. The price includes domestic postage in the United States and air postage to the rest of the world. Back numbers of earlier volumes, are available, in limited number, at the Same price.

We look forward to carrying the torch into the new year.

Sincerely,

For John Tavener and Henry Sostmann

Editors
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NOTICE OF MEETING

THE 7TH INTERNATIONAL SYMPOSIUM ON TEMPERATURE, ITS MEASUREMENT AND CONTROL IN SCIENCE AND INDUSTRY

April 28 - May 1, 1992, Toronto Convention Center

Under the sponsorship of the American Institute of Physics, Instrument Society of America, National Institute of Standards and Technology, National Research Council of Canada

This Symposium, which is held every 10 years, is recognized as the Summit for all thermometrists, and speaks to a range of interests from the most arcane theoretical to practical applications in industry, research, aerospace, biology, medicine ... you name it. It includes cutting-edge research reports and how-to-do review papers. At the last word we had, more than 700 papers had been submitted, and there are also poster sessions. Papers are subject to expert review.

Readers most probably will be familiar with these Symposia, through acquaintance with the Proceedings of past sessions, published under the general title "Temperature, Its Measurement and Control in Science and Industry," and identified by a Volume number with the relevant Symposium. (To avoid confusion, we point out that the Proceedings of the Sixth Symposium resulted in Vol. 5, of the Fifth Vol. 4, of the Fourth Vol. 3... evidently an early Symposium did not publish). The Proceedings in Volume 5 contain 1395 dense pages of text, and Volume 6 should rival this. These Volumes are perhaps the most often referenced of any publication in the temperature literature, and are guarded jealously in every comprehensive library of the literature.

The 7th Symposium will take place in conjunction with an ISA Exhibit, from April 28 through May 1, 1992, at the Toronto Convention Center, Toronto, Ontario, Canada. In addition to technical sessions there will be a manufacturers' exhibition, and Isotech, of course, will be there.

For further information, you may ask it of Ms. Sylvia Ramboz, Temperature and Pressure Section, NIST (telephone 301-975-4800) or Ms. Charlotte Clayton, Instrument Society of America, (telephone 919-549-8411, Fax 919-549-8288). If you cannot attend, you might at least wish to preorder a set of the published Proceedings. It would be nice to see you in Toronto!
The Standard Platinum Resistance Thermometer, acronym SPRT, is the stipulated interpolation instrument for realizing the International Temperature Scale of 1990 between the defining fixed points, over the range from 13.8 K (the triple point of eka-hydrogen) to 961.78°C (the freezing point of silver). The transfer function of the SPRT is electrical resistance as a function of temperature; therefore an accurate measurement of resistance, referred to a fixed resistance base, is an essential component of the measurement chain. This article discusses fixed resistors, and then both traditional and modern means for making the resistance measurement.

1: FIXED RESISTORS

The ohm is now maintained, in most National Laboratories, as a quantum-Hall (QHE) effect device; the Von Klitzing ohm. In the apparatus which allows realization of the QHE ohm, semiconductor devices of standard Hall-bar geometry are placed in a large applied magnetic field at a temperature near 1 K. For an applied current through the device, there are regions where the Hall voltage remains constant, as a function of the fundamental constants $\hbar/e^2$ as the field or the gate voltage are varied. There are a number of such plateaus; the conventional value of the effective resistance of the first plateau is 25 813.807 Ω (1). This value is believed consistent with the SI ohm to within an assigned le uncertainty of 0.2 ppm.

(The use of the QHE ohm in nations which are members of the Treaty of the Meter became effective on January 1, 1990, replacing at NIST the NBS ohm of 1948. The relationship is:

$$1 \ \Omega \ (NBS - 48) = 0.99999831 (NIST-90)$$

Thus the ohm is now realized as a universal constant independent of the variables of experiment. This is much more satisfactory than the earlier definition, where the ohm is a quantity derived from the fundamental SI units as

$$\Omega = \frac{kR \cdot m^2}{A^2 \cdot s^2},$$

or the still earlier definition in terms of the electrical properties of a column of mercury.

Prior to the adoption of the QHE ohm as a standard representing a fundamental constant, the ohm was maintained in most National services as the mean resistance of a bank of 1 Ω resistors (usually 10), which were, or were generally similar to, the 1Ω resistor developed by Thomas at the NBS (2). Because of the cost and complexity of maintaining the QHE ohm, it is highly probable that most laboratories which are not National, and many National Laboratories in smaller nations, as well as scientific and industrial organizations in the private sector, will continue to rely on the Thomas-type 1Ω resistor to maintain the local standard of the ohm, and it is to these that the fixed resistors which are the reference basis for platinum resistance
thermometry will be referred.

The primary requirement for a resistance standard is permanence of value with respect to time and use. (I do not include accurate knowledge of the resistance, since every standard resistor must be accompanied by a valid and up-to-date calibration certificate). (In the unusual case where all measurements will be made using the same fixed resistor and bridge, and there is no need to report a calibration that is to be transferrable to another set of fixed resistor and bridge; that is, where results in terms of bridge units for a specific bridge are all that is desired, stability may be the only paramount requirement). Secondary and highly desirable characteristics are (a) a low and stable temperature coefficient (b) a low thermal e.m.f. with respect to copper in the external circuit (c) a design which permits dissipation of the $I^2R$ heating due to the passage of the measuring current (d) low or zero reactance, which can also be characterized as a fast time constant in response to an impressed input. (d) is of particular interest when the resistor is used as the standard resistor of modern automatic resistance bridges or comparators, most of which operate at low ac frequencies.

As a generality, all resistors which can be considered as reference standards use bulk wire as the resistance element. An exception to this is the resistor design of Vishay, which comprises a fine grid of metal laid as a thick film on a glassy substrate, in such a pattern that the adjustment of resistance to a precise value can be made by physically cutting certain conducting lines. The success of this scheme in resistors intended to be stable standards is not yet proven; there arise questions of, for example, strain developed because of the differing characteristics of the deposited metal and the substrate. These resistors, however, have proven to be very valuable as highly precise circuit elements.

Various alloys are available for the bulk wire resistance element. Perhaps the most important of these is manganin, an alloy developed by Edward Weston in 1889. The composition is 84% copper, 12% manganese and 4% nickel. The resistivity at 20°C is about 48.3µΩ/cm (290Ω per circular-mil-foot). The temperature coefficient of resistance is about ±0.000015 Ω/°C over the normal laboratory range of 15° to 35°C, although it varies from lot to lot for reasons which are not well understood or predictable. It can be adjusted somewhat by heat treatment in fabrication. For precise work, the temperature of the resistor must be noted and a correction made. The calibration certificate of the specific resistor should include the measured coefficients of the correction equation, which assumes standardization at 25°C.

$$R_{t1} = R_{25}[1 + \alpha(t_1 - t_{25}) + \beta(t_1 - t_{25})^2]$$

For properly selected manganin, $\alpha$ generally has a value smaller than 10 x $10^{-6}$, and $\beta$ between -0.3 x $10^{-6}$ and -0.8 x $10^{-6}$. Fig. 1 shows a typical curve of resistance versus temperature for good manganin. The most desirable situation is that the peak of the curve be located very close to the laboratory ambient temperature, so that any effects of $I^2R$ heating have minimum influence on the resistance. A further precaution is to maintain standard resistors in thermostated oil or air baths. Oil baths, in particular, also assist in dissipating any self-heating. The thermoelectric power versus copper is low; 2 to 3 µ/°C.

In constructing manganin resistors, it is particularly important that where the manganin joins internal copper lead wires, the joint be made by welding, or brazing with suitable materials. The components of softsolders can, with time, migrate into the manganin wire structure and cause irreversible alloy (and consequently resistance) changes.
Another resistance wire alloy in common use is known by the trade names Evanohm and Karma. Its major advantage is a high specific resistance, 800 $\Omega$/cm ft, which permits all resistors to be made of wire of larger cross section than manganin, and consequently of better mechanical stability in situations of normal shock, vibration, etc. incidental to use. The composition of the alloy is about 75% nickel, 20% chromium plus a few per cent each of aluminum and copper. The temperature coefficient is about $\pm 0.00002$ $\Omega/\Omega/\degree C$ but there is no peak such as that of manganin. Fig. 2 shows a typical curve for Evanohm.

I cannot comment from personal experience on the resistance stability of Evanohm relative to that of manganin. I can mention that manganin is a solid solution of its constituents, while Evanohm is an intermetallic; that is, some of the elements of the alloy remain as discrete crystals. From experience long ago in using potentiometer wires which contained aluminum, I can report that as surface crystals it is subject to eventual oxidation, which in potentiometers caused local spots of high contact resistance, and in standard resistors may be a source of calibration drift. Nevertheless the Australian laboratory CSIRO has made 1 $\Omega$ Thomas-derivative resistors of Evanohm with remarkably small changes in resistance over a number of years. The composition of Evanohm suggests that all joints to copper be made by welding, since it is difficult to wet chromium and aluminum with soft solders, and the migration problem is probably equivalent to that with manganin.

The basic design of the Thomas 1 $\Omega$ resistor is shown in Fig. 3. Manganin wire of heavy gage is wound on a temporary mandrel in a bifilar fashion with spaced turns. The wire is bare, so that full heat treatment (at 550$\degree C$ in an inert atmosphere) may be applied, as would not be permissible were the wire enamelled or served with a textile fiber serving. After heat treatment, the helix is slipped onto a silk-insulated metal cylinder and sealed into a dry double-walled container. The wire gradually reaches equilibrium with the slight amount of contained dry air.
Such a resistor is capable of stability of 1 part per million over several years. The construction is not optimal for heat transfer, and so any impressed current must be carefully limited. There is some slight effect on resistance from changes in barometric pressure, and the calibration certificate will furnish information about this.

While the 1Ω Thomas-type resistor will be regarded by most users as the reference base for the ohm, it is not a very useful value for most resistance thermometry, where it is more desirable to have a reference resistor whose value is in the vicinity of, for example, the resistance of the thermometer at 0°C. For a 25.5Ω thermometer this might be 25Ω; for an 0.25Ω thermometer, 0.25Ω, with 1Ω another choice. Also, one would not wish to use the laboratory’s standards base as a working standard. Most laboratories will maintain the 1Ω standard and possibly an equivalent 10kΩ standard built to the general Thomas design, and use these to build up and build down, by ratiometric methods, to the working standards of more convenient value.

A sign of working standard which has proven itself through the years is that of Rosa, also known as the NBS-type resistor, shown schematically in Fig. 4. The resistance wire, which is manganin for at least the values of 10KΩ and lower, is insulated with either enamel or a special textile fiber in which cotton and silk are mixed (this mixture said to provide minimal strain to the manganin it covers when the fiber is subjected to changes in ambient humidity). The wire is doubled at its midpoint and wound in bifilar fashion onto an insulated brass bobbin (a material chosen because the thermal expansion coefficient of brass closely matches that of the wire, and because it aids in heat dissipation).

The ends of the winding are brazed to a pair of short heavy copper leads, the free ends of which are connected to massive terminals. Externally, four connections are proved, a potential connection and a current connection to each end of the resistance winding, so that the resistor may be connected four-terminal.

A four-terminal resistor schematic is shown in Fig. 5. The value of the four-terminal resistor is the potential difference between the potential terminals divided by the current through the current terminals, so that external circuitry is not a part of the measured resistance. The potential and current terminals are interchangeable. For both Thomas and NBS-type standard resistors, the potential terminals are usually binding are external resistances; e.g., lead posts and the current terminals are connected into the circuit using massive mercury-wetted amalgam contacts.
A FOUR-TERMINAL RESISTOR. RS is the resistance to be measured. R1, R2, R3, R4 are external resistances; e.g., lead resistances. C1, C2 are current terminals, P1, P2 potential terminals. For an SPRT these are conventionally labeled c, C, t, T respectively.

Fig. 5

The finished winding assembly must be stabilized by heat treatment, and this process cannot be carried out to completion; the temperature at which the wire would be rendered ideally strain-free is higher than the insulation will tolerate. Thus it is of great importance to avoid ever impressing sufficient current on the finished resistor to heat the winding appreciably, or additional annealing may occur, with a permanent shift in value. During the production anneal, the value may decrease permanently by as much as 1% or 2%, and this must be allowed for in the winding length. The final adjustment of resistance is made coarsely by removing wire, and fine adjustment by reducing the wire cross-section, locally, by abrasion.

Rosa resistors are filled with a bland neutral oil, which assists in dissipating and transferring heat. They are equipped with a central well, into which a thermometer is placed to measure, with very close approximation, the coil temperature. A typical manufacturers’ specification for stability is 20 ppm per year, which is, in my experience, highly conservative for a unit which is handled carefully.

Safe operating currents are stipulated by the manufacturer. These values should be posted on labels, and well-known by operating personnel. The use of an air or oil bath will increase the safe operating current limit, as well as provide temperature stability.

As far as I know, the principle supplier in the US of Rosa-type resistors, Leeds and Northrup, has never qualified or made a statement about the ac properties of these or the Thomas 1Ω resistors of their manufacture.

NIST does not at this time offer a calibration of standard resistors which includes a comparison of dc with low-frequency ac characteristics, although, according to a telephone conversation (November 1991) with Norman Belecki of the Electricity Section, it plans to do so "in about a year". The National Physical Laboratory (NPL) of England has been offering this service since 1987. Resistors submitted by Isotech to NPL, which are used in conjunction with ac bridges for thermometry, are reported including a ratio of $R_f/R_{dc}$, where $f = 75$ Hz.

Fig. (6) reproduces a typical calibration report.


NATIONAL PHYSICAL LABORATORY
Teddington Middlesex TW11 0LW England

Certificate of Calibration

STANDARD RESISTOR

No 248712 10 OHM H TINSLEY AND CO LTD

FOR :
Isothermal Technology Limited
Pine Grove
Southport
Merseyside PR9 9AG

REFERENCE:
Order No. 90PO065/10 dated 11 May 1990

BASIS OF TEST:
NPL Measurements Services - Direct Current and Low Frequency Electrical Measurements (1987). Section 3.2

PREVIOUS CERTIFICATE:
None

MEASUREMENTS:
The resistor was immersed in an oil-bath controlled at a temperature of 20.000 ± 0.005°C for at least 2 hours prior to and during the measurement and was measured in a 4-terminal configuration. The power dissipated in the resistor was less than 1 mW.

<table>
<thead>
<tr>
<th>Resistance</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.999 917 ohms</td>
<td>± 0.43 ppm</td>
</tr>
<tr>
<td>* 0.25 ppm</td>
<td>* 0.25 ppm</td>
</tr>
</tbody>
</table>

The uncertainty of the measurement is quoted in two ways:

(1) At "A Confidence Level of at least 95%" - where the individual contributions have been combined in quadrature where appropriate.

(2) As expressed on certificates prior to October 1989 - where the individual contributions have been added arithmetically, "Arithmetic Sum of Contributions".

These uncertainties refer only to the measured value and do not carry any implication regarding the stability of the instrument.

Reference EB 94.69
Checked N.D.
Page 1 of 2

Date of calibration 7 June 1990

Signed [Signature] for Director

This Certificate may not be published except in full, unless permission for the publication of an approved extract has been obtained in writing from the Director. It does not of itself impugn the subject of calibration any attributes beyond those shown by the data contained herein.

ADM/12/97
# National Physical Laboratory

## Continuation of Certificate

**AC/DC Standard Resistor**

No 248712 10 ohm H Tinsley and Co Ltd

## Results:

<table>
<thead>
<tr>
<th>Test Frequency (Hz)</th>
<th>R_f/R_{dc}</th>
<th>1: Confidence Level at least 95%</th>
<th>2: Arithmetic Sum of Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>1.000 000</td>
<td>± 0.9 ppm</td>
<td>± 2.4 ppm</td>
</tr>
</tbody>
</table>

\[ \upiota : \mu \text{H/\Omega} \]

0.10 ± 0.015 \( \mu \text{H/\Omega} \) = ± 0.02 \( \mu \text{H/\Omega} \)

The resistor was inductive.

The uncertainty of the measurement is quoted in two ways:

1. At "A Confidence Level of at least 95%" - where the individual contributions have been combined in quadrature where appropriate.

2. As expressed on certificates prior to October 1989 - where the individual contributions have been added arithmetically. "Arithmetic Sum of Contributions".

These uncertainties refer only to the measured value and do not carry any implication regarding the stability of the instrument.

---

Reference: E5A 534.198
Checked: 7557
Date of Calibration: 18 June 1990
Page 2 of 2

Signed: [Signature]
2: STANDARD RESISTORS USED WITH ALTERNATING CURRENT

Many modern devices for measuring the resistance of an SPRT operate in a semi-automatic or automatic fashion, based on principles which require that the signal received from the bridge be ac. Usually it has been possible to arrange circuitry allowing the frequency to be very low, with an upper bound of 400 Hz and a lower as low as 15 Hz. (I except an experimental bridge of Cutkosky which operated at ½ Hz, but which was never commercially available.)

The reactances of reference resistors are a function of their inductances (from the area included within the winding loop where the wire is doubled) and distributed capacitance. In general the inductance is small but the capacitive reactance is not, although it may be reduced by such devices as dividing the coil into sections. Reactance may include effects of the mandrels on which the winding is supported. The time constant of a resistor may be expressed as

$$\tau = \frac{L - CR^2}{R}$$

and may also be expressed as the time required for the current to reach 1/є of its final value after a fixed voltage is impressed. Obviously, for a-c bridge service, the time constant must be short enough to allow the full value to be achieved within 1 ppm or 0.1 ppm.

Details of design can be used to reduce residuals; for example splitting the wound coil into two sections connected in series can reduce the capacitance by a factor of 4. Many designs other than that of Fig. 4 have been proposed to eliminate residuals over a desired band of frequencies. These include flat single-layer windings an card-shaped mandrels, for example of sheet mica. Produced by, for example, Electro-Scientific Industries of Portland, Oregon, these have formed the basis of a large number of commercial bridges, decade boxes, and the useful and familiar Dekapots and Dekastats. Other approaches include windings which pass through a slotted ceramic core and reverse direction with each turn, etc. Difficulty in manufacture has prevented these from becoming widely used. High resistance elements have been produced commercially in which the winding is a flat woven web, or patch, with a resistance-wire warp and a textile-fiber weft, and these have been used for many years in certain Leeds and Northup standard resistors, above the range of interest for platinum resistance thermometry.

A number of workers in the last several decades have attempted to design standard resistors to give the same value for low-frequency ac (dc to several kH). A successful configuration has been described by Wilkins and Swan (3). This general configuration is available from H. Tinsley & Co. Ltd. (4). It is a Tinsley resistor which is the subject of the NPL Calibration Report shown in Fig. (6).

Wilkins identifies a number of factors which determine the frequency characteristic of a resistor. These include thermoelectric effects resulting from the nature of the resistance wire alloy, inductance and capacitance of the resistor resulting from the arrangement of the resistive element, and eddy current and dielectric losses resulting from the mounting and housing and from the disposition of current and potential lead wires. All of these require consideration in design for ac use.

Many resistive alloys have thermoelectric properties versus copper. When alloy to copper junctions are not at the same temperature, these effects present themselves as (a) Seebeck effects, in which a voltage is generated in opposition to the voltage impressed upon the resistor for the Bake of measurement (b) Peltier effects, in which the passage of a direct current through a junction of dissimilar metals causes heating or cooling at the junction (c) Thompson effects, in which a voltage is developed between points along a wire of uniform composition with a temperature gradient along its length. These effects may combine in various senses and serve to make a measurement of pure resistance indeterminate. In these cases, the true value of
resistance is measurable only at the instant that the circuit is energized, and another value may be measured when the circuit values have stabilized. The indications for resistor design are that (a) resistance wires with low Siebeck coefficients should be chosen (b) the physical design should exert every effort to maintain the alloy-to-copper and the winding itself in an isothermal condition.

In general, the reactance of low-ohm (up to 500Ω) resistors is inductive, and almost any reasonable value of capacitance is acceptable. It is, however, desirable to keep the inductance low, since the phase angle between applied voltage and current is largely due to the ratio L/R. Low inductance indicates as short as possible a length of wire in the bifilar helix; a condition which, for a given resistance, requires wire of small diameter. This is at odds with mechanical stability, which argues for large diameter wire, and so a compromise is required.

With careful consideration of all the above factors, Wilkins has produced resistors whose dc and ac resistances are the same within 0.1 ppm to frequencies as high as 1.6 kHz.

3: AC: POSSIBLE EFFECTS ON SPRTS

An SPRT winding is not mechanically or electrically dissimilar from the winding of a standard resistor. It is a spaced bifilar winding in which the current path is in one direction for approximately half of the winding and reverses for the other half, so that it approximates a non-inductive winding, but may be capacitive. Many precise measurements of both Leeds and Northrup pattern SPRTs and those manufactured by Isothermal Technology seem to indicate that these effects are sufficiently small so that the measurement deviation due to electrical reactance is not more than 0.1 part per million at low impressed frequencies, compared to d-c measurements.

At high temperatures other a-c effects have been noted. Studies of the best insulations used for the formers an which SPRT windings are supported indicate that the degradation of the insulating properties of quartz and sapphire is marked. I have measured insulation resistance in a thermometer of 120 MΩ per square at 960°C, which drops to about 20 MΩ per square at 1100°C. 20 MΩ of random shunt resistance cannot be ignored, and this effect is a prominent reason why ITS-90 terminates the SPRT range at the silver freezing point (961 °C) instead of the gold freezing point (1064°C).

Such a shunt effect would be, of course, as undesirable with dc as with ac, but much of the effect seems to be due to a long time-constant polarization, so that resistance rises over a time which may be measurable in minutes. Thus the recovery of most of the insulation resistance would take place with a direct current impressed, but might not within the reversal time of an alternating current.

4: DC BRIDGES FOR RESISTANCE THERMOMETRY

Resistance measurements can be made by deflection (magnitude of the unbalance of a circuit which is balanced at some value) or by balance. Deflection methods are never used in the precise determination of resistance (except as the deflection of the galvanometer is used to further quantify the last place on the bridge dials).
An elementary (Wheatstone) bridge is shown schematically in Fig. 7, where A and B are fixed resistors (often of identical value, in which case the bridge is said to be "equal-arm", a resistance decade S, and an unknown resistance to be measured, X. At balance, when the unknown resistance is balanced by the decade resistance (assuming A = B), the potential drop from Junction 1 to Junction 2 is equal to the potential drop from Junction 1 to Junction 4, so that \( i_{abA} = i_{xsX} \) and \( i_{abB} = i_{xsS} \). These equalities can be expressed as

\[
\frac{A}{B} = \frac{X}{S}
\]

which is the equation of balance for the Wheatstone bridge. At this balance, no current flows in the galvanometer arm G.

The equalities of the balance condition include the entire bridge circuit, including any external lead wires which extend to the resistance, X, which is the subject of the measurement. These external resistances may be negligible, for example if X is very large in comparison with \( R_{11} \) and \( R_{12} \), but in an elementary bridge, they are always a component of the measurement in series with X. In industrial resistance thermometry, lead resistances can be partially compensated, or almost completely compensated under specific restrictions, (e.g., by inserting a dummy loop of lead wire in the opposite side of the bridge), but must be eliminated for precise and standards-quality resistance thermometry. Figs. 8(a) and 8(b) show two methods for making such connections. Obviously, the degree of compensation depends upon the other resistances in the circuit; for example, compensation is more closely approximated if the bridge is constructed with equal ratio arms.
Bridge connections for an industrial platinum resistance thermometer, providing partial lead resistance compensation. In 8A, (a 3-wire thermometer) L1 is in series with the battery, where it is effectively not a part of the bridge balance circuit. L2 is in series with RA, and L3 in series with the sensor. In 8B, (a 4-wire thermometer) L1 and L2 are in series with the sensor, while a dummy loop (L3 and L4) comprising a length of lead wire equal in resistance to L1 + L2 is in series with the bridge balance resistor. The degree of compensation depends upon the bridge values and the bridge unbalance.

5: D-C BRIDGES: THE MUELLER BRIDGE

The most commonly used d-c bridge for four-terminal measurements of standard platinum resistance thermometers, from the time of its design in 1916 until the advent of more modern inductive bridges, was developed by Mueller at the NBS (5). McLaren’s seminal work in developing the metal freezing points as calibration standards was done with an L&N Mueller G-2 Bridge (Mac calls it a G-2 ½, the ½ to recognize a least decade he added, and my own work an the gallium melt point was done with a Rubicon version of the G-2. The Mueller bridge represents a modified Wheatstone bridge with a range up to 81.111Ω, 111.111Ω, or 422.1111Ω (6) full-range.

(Anyone visiting NIST will be interested to have a look into the Museum, which is rather well concealed behind a door to the right of the main entrance to the Library, in the Administration Building. Many beautiful original devices are there an display, and among them is Mueller’s first bridge, which he made with a sheet of marble as its top panel).

The bridge is always used with equal ratio arms of moderate individual resistance, e.g., 500Ω or 3000Ω. An small slide wire is provided which is used to balance these resistances exactly, by interchanging them. Once the arms are equal, the zero resistance value can be determined precisely. Commutators are supplied for these adjustments.

Consider the bridge circuitry shown in Fig. 9. (A complete diagram of the Leeds and Northrup G-3 Mueller Bridge is shown in Fig. 10). The four lead c, C, t and T of the thermometer are connected as shown, and are integrated into the bridge circuitry as follows:

In the commutator switch Position of the left-hand circuit, lead c connects into the battery circuit, where its resistance is of no consequence. In the commutator position of the right-hand circuit, lead t is in the battery circuit. Potential leads C and T are in opposite lower arms of the bridge circuit, and are switched to the alternative arm by the commutator. Thus battery leads are exchanged and connections to the decade arm and the fixed arm of the bridge are exchanged simultaneously. The commutator is a switch whose contacts are mercury-wetted, which, if they are clean and in good condition, will add contact resistance resistance of, at most, several micro-ohms.

Fig. 9 – A schematic Mueller Bridge
Fig. 10

The complete circuit of the Leeds and Northrup G-3 Mueller Bridge. The least dial is 10 μ. Bridge arm resistances of 500 or 3000Ω may be chosen. Note that the x0.1Ω decade is subtractive. (Courtesy Leeds and Northrup Co., North Wales, Pennsylvania)
Since the bridge ratio is 1:1, if the C and T leads are equal in resistance, they will cancel each other, and the net resistance added to the X arm of the bridge is only the resistance of the thermometer coil. At the level of precision required of this measurement, leads C and T cannot be assumed to have equal resistance. A reversal of leads C and T would result in a slightly different balance. The correct measured resistance of the thermometer coil alone, which is what is wanted, is as follows, where \( R_1 \) is the result of the first balance and \( R_2 \) is the result of the second balance:

\[
R_1 + C = RT + T, \quad \text{or} \quad R_1 = RT + T - C
\]

where \( RT \) is the resistance of the thermometer coil alone, and

\[
R_2 + T = RT + C, \quad \text{or} \quad R_2 = RT + C - T
\]

The average, then, is

\[
\frac{R_1 + R_2}{2} = RT + T - C + RT + C - T
\]

\[
= \frac{2RT}{2} = RT
\]

In the manufacture of most SPRTs care is taken to adjust lead resistances so that the difference in balance between the normal and reversed position of the commutator switch requires, usually, adjustment of only the lowest dial.

Two design characteristics of the Mueller Bridge are elegant enough to be worth noting. The first is the nature of the decade switches, which must be constructed so as to be free from unwanted contact resistances, even though on the lowest dial the increment of resistance (on the L&N G-3 Bridge) is 10 \( \mu \Omega \) (0.00001 \( \Omega \)). No physical switch has contact resistances which would not represent an uncertainty of many times that level (the best switches, properly maintained and lubricated, are not better than 0.001 \( \Omega \) uncertain), and the friction of switching frequently generates spurious and transient thermal emfs. Nor is it possible to make fixed decade resistors of micro-ohm values. The lower decades of the Mueller bridge, \( x 0.1 \Omega \) and lower, employ Waidner-Wolff decades.

When a shunt is applied to a resistor, the change in resistance \( \delta R \) is

\[
\delta R = \frac{R - RS}{R + S} = \frac{R^2}{R + S}
\]

The reduction in resistance from that of the unshunted resistor is

\[
(10 - n)\delta R
\]

\[
\frac{R^2}{R + S} = (10 - n)\delta R
\]

and the shunt required is

\[
S = \frac{R^2}{(10 - n)\delta R} - R
\]
Fig. 11 shows a Waidner-Wolff decade, in which a fixed series resistor, Rs, is shunted by shunts, R1...R10, that can be varied in 11 steps from 0 to infinity. Rs° should be exactly divisible by all the integers below 10. One possible value for Rs°, used in the Figure, is 50.4. The minimum shunt resistance is obtained when the switch is set at 0; for the X0.0001 Ω decade, R1 = 50.4 - √0.0504.

### The Effect of this Arrangement

The effect of this arrangement is to place a large resistance in series with any sliding switch contact, so that variations in contact resistance are negligible. The sum of the decades in their zero positions is, however, not zero but is the sum of the resistances in series with the sliding contacts, in the example of Fig. 11, 9.167 Ω, and a compensating resistor is inserted into the opposite leg of the bridge to exactly balance this residual resistance.

A second feature of the Mueller bridge is provision for self-calibration. Since there are 11 positions an each decade switch (0 through X = 10) any resistance which is the maximum resistance of a dial is the resistance of the first step of the next higher dial. The bridge can be self-calibrated in terms of internal bridge units using no more equipment than a stable decade resistance box, and to calibrate in terms of absolute ohms, only one standard resistor, preferably 10 Ω, is necessary. The technique is described in manufacturers' manuals. It consists simply in

---

**Fig. 11 A WAIDNER-WOLFF DECADE OF A MUELLER BRIDGE**

Resistors R1 through R11 are the same for all decades. They shunt Rs, adding one increment of resistance per dial step. The values shown are one of a number of possible sets of value.

For all decades:  

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<th>R1</th>
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<tr>
<td>R2</td>
<td>5.6 Ω</td>
<td>x 0.1 √50.4 50.4 - √50.5</td>
</tr>
<tr>
<td>R3</td>
<td>7.0 Ω</td>
<td>x 0.01 √50.04 50.4 - √50.04</td>
</tr>
<tr>
<td>R4</td>
<td>9.0 Ω</td>
<td>x 0.001 √0.504 50.4 - √0.504</td>
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<tr>
<td>R5</td>
<td>12.0 Ω</td>
<td>x 0.0001 √0.0504 50.4 - √0.0504</td>
</tr>
<tr>
<td>R6</td>
<td>16.8 Ω</td>
<td>Note that with all dials set at 0, the value of the</td>
</tr>
<tr>
<td>R7</td>
<td>25.2 Ω</td>
<td>decade string is not zero. This non-zero resistance</td>
</tr>
<tr>
<td>R8</td>
<td>42.0 Ω</td>
<td>is balanced by an equal and trimmable resistor in</td>
</tr>
<tr>
<td>R9</td>
<td>84.0 Ω</td>
<td>the opposing arm of the Bridge.</td>
</tr>
<tr>
<td>R10</td>
<td>252.0 Ω</td>
<td></td>
</tr>
<tr>
<td>R11</td>
<td>∞</td>
<td></td>
</tr>
</tbody>
</table>

If the ratio R°5/ΔR is made the same for all decades, then identical sets of fixed coils per step may be used for all decades. The resistances which must be put in series with the R1, when Rs° = 50.4, are shown in Fig. 11.
first setting a decade dial to 1 and the next lower decade to 0, using the next lower dials to balance an appropriate input resistance; and then, without changing the external resistance, setting the decade dial to 0 and the next lower dial to X, rebalancing with the lower dials, and noting the difference. Thus each step of the bridge dials can be compared with the next lower dial, and finally the lower dial can be calibrated in terms of galvanometer deflection.

6: DIGITAL OHM METERS

It is tempting to think of multi-digit high-resolution ohm meters as readouts for SPRTs. In general, they are not satisfactory. Most 8½ and 9½ digital ohm meters present much more current through the thermometer than the 1 mA level which is the accepted level for calibration, and none that I know of permit two current levels (say 1 mA and $\sqrt{2}$ or 1.414 mA) which would allow the desirable extrapolation to zero-power resistance, to eliminate the effects of $I^2R$ heating. (As an aside, this qualification becomes even more important for a user who measures the resistance of industrial temperature sensors of low dissipation, such as small industrial PRTs and thermistors).

7: A PRECISION CURRENT COMPARATOR WITH DC THERMOMETER EXCITATION

All conventional dc bridges, such as the Mueller Bridge, depend upon a number of decades of precision fixed resistors. Such resistors are subject to drift in value, due to a number of factors; strain or the relief of residual strain, impressed current, atmospheric and other contamination. Recalibrations are not difficult to do, using equipment generally available in the laboratory and one stable fixed resistor of known characteristics, but must be done at appropriate and perhaps frequent intervals. The resistors themselves have temperature coefficients. Attempts to eliminate temperature effects by thermostating the bank of resistors leads to the generation of thermal e.m.f.s at the junctures of resistance alloys and copper circuitry wiring; the tradeoff is the need to make temperature corrections.

An alternative to decade resistors is decade inductors. Toroidally wound inductive dividers and transformers provide a means for generating very accurate ratios of voltage or current equal to an integer ratio of turns. Since there is no such thing as dc inductance, bridges which use inductors require ac excitation, which may be at low frequencies. In theory, at least, the position of a tap on a well-made inductor is fixed and stable; if the entire inductor is isothermal the tap position should be effectively unchanged with environmental changes. Any thermale generated are dc and cancel in ac circuitry.

Based on the work of Kusters et al (7) at the National Research Council (Canada), Guildline developed its Model 9975 Precision Current Comparator. This comparator is unique among modern bridges in that, while the inductors require ac, the Signal applied to the galvanometer is dc. The principle is simple, although the execution is sophisticated, and is illustrated in Fig. 12. There are three windings on a highpermeability toroidal core, suitably shielded electrostatically and magnetically. If ampere turns $I_1N_1$ and $I_2N_2$ are equal and opposite (that is, in a condition of balance) there will be zero flux in the core and consequently zero voltage induced in the detector winding. However in practice, the primary and secondary currents of a current transformer are never exactly equal. A special core design makes it possible, in the 9975, to ad just to zero flux with a small compensating current.

The operation is as follows. Current from a power supply flows through an adjustable number of turns of the comparator ($N_x$) and through the thermometer ($R_x$). A second current flows through a fixed number of turns ($N_s$) and through the reference resistor ($R_s$). When the bridge is in balance, both the net ampere-turns imposed on the comparator cores, which are indicated on an ampere-turn balance meter, and the difference between the voltages across the thermometer and the reference resistor, as measured by the sensitive light-beam galvanometer, must not
change as the currents through both are reversed. Reversal may be automatic, at a selected rate, or manual. This bridge is capable of measurements of 1 part in 10 million, and its expected accuracy and stability is 2 parts in 10 million. It requires manual manipulation of the decade dials; its balance and rebalance is not automatic.

Fig. 12

The circuit schematic of the Guildline Model 9975 Direct Current Comparator.
(Courtesy Guildline Instruments Inc., Orlando, Florida and Smith Falls, Ontario, Canada)

8: A NEW AUTOMATIC DC CURRENT COMPARATOR
A relative newcomer to the field is the Measurements International Model 6010A DC Resistance Thermometer Bridge (8), announced at the annual meeting of the National Conference of Standards Laboratories, Albuquerque, N.M. in 1991. The bridge appears to be a dc current comparator rather like the Guildline 9975, except automatically balanced. (It does not seem to have the capability to operate in the off-balance mode, needed to make a chart recorder sweep). According to Duane Brown, VP Operations, the 2σ uncertainty of the bridge is better than 0.1ppm + 1 least significant bit and linearity and resolution are specified as 0.01ppm. The measurement range is 0.1 Ω to 10 kΩ full-scale, and provides ratio ranges from 0 to 10 Rx/Rs. A suitable number of thermometer current choices are provided, all of which may be multiplied by √2. I have not had an opportunity to see or use this bridge.

AN AC AUTOMATIC OR MANUALLY-BALANCED BRIDGE

Automatic Systems Laboratories has developed a line of bridges which can be used in a truly automatic-balance mode, or manual balance may be selected (9). (The latter is most handy to have, for it is often desirable to operate a bridge in a condition of unbalance approaching balance; e.g., when a chart record is being made of a rising temperature).

The ac carrier of the F-17 bridge is fixed at 1 ½ line frequency; for 50 Hz supplies at 75 Hz, and for 60 Hz supplies at 90 Hz. This choice allows maximum rejection of noise from the line and from active circuit components, while providing maximum detector bandwidth. The more sophisticated F-18 operates at ½ and 1 ½ line frequency (25 Hz and 75 Hz for 50 Hz supplies and 30 Hz and 90 Hz for 60 Hz supplies) selectable. This feature allows the estimate of any effects on the measurement due to carrier frequency, and extrapolation to dc where necessary.

A block diagram of the F-17 and F-18 bridges is shown in Fig. 13. A stable ac signal is produced by a carrier generator current source. This drives current through the Standard resistor and the unknown resistor, which are connected in series. The voltage generated across Rs is used as the reference signal to excite the Input windings of a multistage inductive divider. The inductive divider's secondary output is compared with the voltage appearing across the unknown resistor Rx, in this case, the SPRT, by the detector circuitry. The inductive divider acts as a precision ratio transformer. Its taps are adjusted to balance (that is, to bring to zero) the output to the detector circuit. At balance, the voltage from the inductive divider is exactly equal and opposite to that appearing across Rx. The output of the inductive divider is also a precise ratio of the voltage across Rs. Since the current flowing through Rs and Rx is identical, the ratio set on the inductive divider is equal to the ratio Rs/Rx.

The nominal accuracy of the F-17 bridge is 1ppm, and of the F-18, 0.1ppm. The F-18 is optimized specifically for SPRT values of 100, 25.5, 2.5 and 0.25 Ω. The F-18 has 7 ½ decades, and reads resistance ratios over the range 0.000; 000; 0 and 1.299; 999; 9. A generous selection of operating sensitivities and of thermometer currents (from 0.1mA to 50mA rms, (F-18) including a √2 multiplier) are supplied.
Fig. 13

THE ASL F-17 AND F-18 AUTOMATIC BRIDGES
Courtesy Automatic Systems laboratories Ltd.

IMPORTANT REFERENCES

In this text, I have relied, as I have for many years, upon two important references on fixed resistors and resistance measurement. These are:


FOOTNOTES


(4) [H. Tinsley Ltd, Standards House, Croyden, Surrey, CR0 4RR, England]


(6) Leeds and Northrup Models 8067 (G-1), 8069B (G-2) and 8071B (G-3) Mueller Bridges, respectively. [Leeds and Northup Company, North Wales, Pennsylvania USA]


(8) [Measurements International, PO Box 2359, Prescott, Ontario, Canada and SW Murray Boulevard, Beaverton Oregon 97006, USA]

(9) Models F-17 and F-18 [Automatic Systems Laboratories Ltd., 28 Blundells Road, Bradville, Milton Keynes MK13 7HF, England]
These tables provide the fees charged for calibration and an interpolated calibration report by a number of institutions offering this service. The fees are accurate to the best of our information, but are presented informally and should be checked with the Institution prior to purchasing services. A blank space for a specific range indicates that the service is not offered, that the fee has not been established, or that our information is incomplete.

The following institutions are shown:

United States National Institute for Standards and Technology, Gaithersburg, Maryland
England The National Physical Laboratory, Teddington, Middlesex, England
Italy Istituto di Metrolgia "G. Colonnetti", Torino, Italy
The Netherlands Van Swinden Laboratorium, Delft, The Netherlands
France CET/LCIE, Dardilly, France
Canada The National Research Council, Ontario, Ottawa, Canada
Isotech NAMAS Isothermal Technology Ltd., Southport, Merseyside, England

(CALIBRATIONS AT ANY OF THESE INSTITUTIONS SATISFY TRACEABILITY REQUIREMENTS TO ANY OTHER)

The following currency conversions have been used as a close approximation:

1 Pound sterling = $1.65 US
1 Netherlands florin = $0.51 US
1 French franc = $0.18 US
1000 Italian lira = $0.81 US
1 Canada dollar = $0.88 US

(Source- The Wall Street Journal, December 1, 1991)
### Ranges Above 0°C Costs in National Currency

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### Ranges Below and Above 0°C Costs in National Currency

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(*) Dr. Ronald Bedford of NRC advises me that these prices are in process of revision, and will perhaps double. The new schedule will include all ITS-90 definite fixed points except mercury, which latter should be operational in 1992. Several secondary points (notably Cd and Sb) are also available.

(*) Please see footnote on the cost and status of calibrations in Canada on the previous page.
ABSTRACT

The International Temperature Scale of 1990 (ITS-90), which extended the range of the Standard Platinum Resistance Thermometer (SPRT) from the previous upper limit of 630 °C (the freezing point of antimony) to 962 °C (the freezing point of silver) has required the development of new types of high-temperature SPRT (HTSPRT), and new techniques for using them. Some of these new ideas have been described in past issues of this Journal [1] and in other literature.

The SPRT has been used in laboratory temperature measurements for so many years [2] that practice in handling them has become almost automatic; their care and management are part of our nature. It is difficult but necessary to recognize that HTSPRTs, because of the range of temperatures to which they are subjected, require techniques and precautions which must be newly learned, are only partially understood at this time even by experts, and are the subject of continuing study. We are all going to have to abandon some preconceptions, and learn what is in many regards a new art. This Journal will do its best to keep its readers informed of these new ideas.

The following is a summary (with the permission of the speakers) of a Workshop held at the Conservatoire National des Arts et Metier, 292 Rue St. Martin, 74151 Paris, France, in September, 1991, organized by the Institut National de M6trologie and supported by Imeko - TC 12. We understand that the printed Proceedings of the Workshop may be had by requesting them from CNAM at the above address. This summary will relate matters of interest with regard to the use of HTSPRTs. A complete list of papers is given in [3].

A REPORT OF THE DISCUSSIONS

From a technical point of view, and with regard to HTSPRTs, the papers of Drs. Marcarino [4] and Ancsin [5] proved most stimulating. Marcarino reported that, even after annealing at the silver point, further annealing of HTSPRTs, of about 2mK, occurred during the first 4 hours at the aluminum point. Repeating the measurements indicated no further change. Ancsin told us that HTSPRTs require up to 14 days to stabilize to 1mK/day at the silver freeze point, and up to 50 or 60 cycles to stabilize against thermal cycling. His work consisted in reducing the thermometers from 950° to 450°C at four rates; 500°C, 200°C, 55°C and 14°C per hour. Only at 14°C per hour was the water triple point resistance completely reproducible. Repeating the work from an upper temperature of 800°C gave similar results, and only when the upper temperature was limited to 650°C did the cooling rates seem not to affect the water triple point resistance.

On fast quenching (up to 10 000°C per hour, such as would be incurred when the thermometer is removed from the furnace at 950°C into ambient) water triple point resistance shifts as high as 7 mK were observed, while no shift was observed when the thermometer was quickly moved from 450°C to ambient.

The shift could be removed completely by soaking the thermometer at 950°C, and then reducing its temperature at 14°C/hour or less to 450°C, where it is safe to remove it from the furnace.

Marcarino reported similar experiences. He agrees that, in order to prevent quenched-in crystal-lattice vacancies, a cooling rate of 14°C - 15°C/hour to 450°C or 500°C is the maximum
This rate is perhaps impracticable for the working Laboratory. The Consultative Committee on Thermometry, in its Monograph “Supplementary Information for the International Temperature Scale of 1990” [6] recommends a cooling rate between 660° and 450°C of 100°C/hour, and is silent regarding higher temperatures. (It would seem, in the light of Ancsin's and Marcarino's work, that the CCT cooling rate may be excessively high). A shift of several mK may be a fair price to pay for an acceptably quick measurement. At any rate, the thermometer may be restored to its original state, when Laboratory time permits, by soaking for a period of several hours at 950°C and then bringing it down to 450°C or so at a rate of 14° to 15°C/hour or slower. This suggests that the furnace used for this purpose should have a controller capable of setting and automating a rampdown rate of that order.

Ancsin's experience also suggested that it required up to 2 weeks at the silver point for the HTSPRT to settle down to drifts of less than 1 mK/day, and up to 50 temperature cycles.

Marcarino shared an experience with accidental thermal gradients. The bottom heater in his 3-zone furnace failed, so that the sensing element was at a lower temperature than the lead wires and the interior of the upper portion of the sheath. Normally, impurities in the internal gas collect at the upper (cooler) end of the sheath; in this case, they seem to have condensed on the element itself. The platinum of the sensing element was effectively poisoned, resulting in a substantial shift. Placing the thermometer in a thermal field with a high negative vertical gradient (element hotter than the other end of the sheath) moved surface contamination back up the sheath toward the handle, and restored the thermometer partially to its original condition.

The speakers agreed that slow removal of an HTSPRT from a silver cell was not good practice, since at some point the measuring element would be in a high thermal gradient. It seemed to be the consensus that, after an aluminium or silver plateau measurement, the HTSPRT should be quickly removed to another furnace at the aluminium or silver temperature. The design of that furnace, also, must be such that the sensing element of the HTSPRT is not cooler than the rest of the thermometer, implying that the furnace be 3-zone, or that it use a heat pipe (as does the Isotech Model 17702) for vertical isothermality.

Much of the rest of the Workshop was concerned with allocating uncertainties to various measurements. A number of computerized or spread-sheet proposals were presented and discussed. The general discussion seemed preoccupied with two uncertainties:

1. At $W = 1.000000$, no uncertainty exists, by Scale definition. This is the condition of $R_o = R_t$ where $t = 0.01°$C. Uncertainties are introduced only when a thermometer is introduced.

2. At the triple point of water, $t = 0.01°$C, an uncertainty is introduced by the piping of light energy down the inside glass wall of the water triple point cell [7]. George Bonnier estimated this as 0.2mK. Martin de Groot informally presented some information that he had measured this uncertainty as high as 3 to 5mK when light was freely admitted, and 1mK when only restricted light could reach the cell.

This stresses the importance of complete darkness around the water triple point cell. It is customary to assure this by covering the cell with an opaque black cloth during measurement. An interesting test would be to sandblast or otherwise roughen the surface of the glass well, to see if any difference were obtained. Bonnier’s detailed estimate of the components of uncertainty for the realized water triple point are shown here:
BUDGET OF ERRORS FOR THE WATER TRIPLE POINT

<table>
<thead>
<tr>
<th>Type A error component</th>
<th>( s = 0.07 \text{ mK} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type B error components</td>
<td>Upper limit of ( \delta t )</td>
</tr>
<tr>
<td>B1: Electrical measurements</td>
<td>0.1</td>
</tr>
<tr>
<td>B2: Hydrostatic effects</td>
<td>0.01</td>
</tr>
<tr>
<td>B3: Short-term PRT, repeatability</td>
<td>0.01</td>
</tr>
<tr>
<td>B4: PRT self-heat</td>
<td>0.1</td>
</tr>
<tr>
<td>B5: Spurious heat flux</td>
<td>0.2</td>
</tr>
<tr>
<td>B6: Chemical impurities</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Combined uncertainties (1σ level) \( \sigma_{\text{water}} = 0.15 \text{ mK} \)

Last, some of the delegates felt that the Pt-Pd or Pt-Au thermocouple was capable of measurements of 10mK uncertainty, and had the advantage of being cheaper and more robust than HTSPRTs. (Thermocouples made of elemental metals have the advantage over R or S thermocouples, or base-metal thermocouples, that there should be no inhomogeneities due to the migration of the alloying material in the alloy leg). However papers by Pommelc and Pokhodun persuaded me that to obtain 10mK uncertainties involved as many uncertainties, precautions and special procedures as with the 0.25Ω HTSPRT).

FOOTNOTES


   J. Ancsin, *Quench-pannealing of PRTs*

1. Wessel, *Propagation of uncertainties calculated by a PC spreadsheet.*

H. Ronsin, E. Renaot, Y. Hermier, W. Mou, *About the Propagation of uncertainties on fixed point temperature measurements between -190° and +420°C.*

K. Riski, T. Wekström, G. Bergstrom, *Propagation of errors in fixed point calibrations in the ITS-90 temperature range; -190° to +960°C.*


J. Tavener, *“A NAMAS Laboratory” - example of a national calibration service facility.*

G. Bonnier, A Renaot, M. Elgourdou, H. Ronsin, *Uncertainties in calibration of PRTs against temperature fixed points.*


J. Y. LePommelec, G. Bonnier, *Thermocouple calibration: uncertainties linked with the lack of homogeneity of wire metal.*


[5] Dr. J. Ancsin, National Research Council, Ottawa, Ontario Canada


[7] This effect was first pointed out, many years ago, by E. McLarin, in the Canadian of Physics. Unfortunately I do not have the reference.
THE GALLIUM WATCHDOG

by David Ayres, Isothermal Technology Ltd.

ABSTRACT

This paper describes the use of the gallium melting point, a fixed point of the International Temperature Scale of 1990 (ITS-90), as a means for assuring quality of comparison calibrations of industrial platinum resistance thermometers, by checking the comparison calibration against one fixed point. The method is easy, and economical of time, to use.

DISCUSSION

In our Laboratory we calibrate Standard Platinum Resistance Thermometers (SPRTs) against the fixed points of the ITS-90, and, usually, Industrial Platinum Resistance Thermometers (IPRTs) by comparison with superior thermometers. My own specific interest is in comparison calibrations.

For all thermometers, I use the water triple point to establish 0°C, extrapolating from 0.01°C. In modern apparatus the water triple point can be made far more continuously available to the calibrator than can the ice point; in our apparatus, (1) we can keep the water triple point for weeks and months, so that this most fundamental calibration point is always and immediately available for use, with no preparation or ritual. In addition, while we can expect accuracy an order of 2 to 5mK from a bath of water and ice, our confidence in the water triple point is about 0.015 to 0.20mK.

At other temperatures, we compare the PRT to a suitable standard thermometer, which may be an SPRT or may be a "like" standard. A "like" standard is a thermometer which resembles in all possible detail the PRT to be calibrated, except that it has been so constructed that it can be calibrated in fixed point cells. (For example, a "like" standard may require a smaller diameter, a longer length, ceramic-clad rather than Teflon-clad lead wires; but every effort is made toward thermodynamic similarity.) We make our comparisons in chilled or heated liquid baths, dry block furnaces or fluidized aluminium oxide baths, as required by the calibration range. A typical set of test temperatures, from which a selection may be made or all may be used, is -50°C, 0.01°C, 232°C, 420°C and 660°C. We prefer to use test temperatures in the immediate vicinity of the fixed points of ITS-90, so that the prescribed interpolation algorithm can be used without too much arithmetical disparity.

In the calibration of SPRTs at fixed points, it has long been practice to do what is called "overdetermining" the thermometer. This means that, if the interpolation algorithm requires five data pairs of temperature versus resistance, six are measured. Then the five are used to find an interpolated resistance value for the sixth temperature, so that the calculated and the measured resistance can be compared. The difference, if any, is an immediate check upon the quality of the measurements of the five points.

I have established the same practice in making important comparison calibrations, by using the melting point of gallium as the overdetermination point.

The primary argument (there are others) for comparison calibrations is speed and economy. Often a large number of thermometers and measurements are involved. Fixed points require time from the laboratory day to establish, and the technique is not really suitable to high throughput. However these comments to not apply to the gallium point. Using a gallium cell in an automated melt apparatus (2) it is possible to start the melt with a timer set an hour before
the laboratory day begins, be upon the melt plateau when we come to work, and use the cell for thermometer calibration all day, with no more fuss or effort than required by our comparison baths or furnaces. The melting temperature of pure gallium is 29.7646°C, and our confidence in that temperature is better than 200 µK. (3)

I find that I can use the data in two ways. The first way is to calibrate a PRT at the water triple point and at the gallium point only, and then, using the ITS-90 equation for interpolation between these points, extrapolate to 660°C. The long extrapolation is possible only because of the extreme precision of realization of the two calibration points, and gives a very good guide to what to expect at any other points. As an example, for a Model 909/25 Standard Platinum Resistance Thermometer:

| Extrapolated values using \( R_{wtp} \) and \( R_{ga} \) measured (Equivalent °C) (°C) |
|---|---|
| 231.928 | 231.928 |
| 419.5195 | 419.527 |
| 660.3230 | 660.323 |

Here, I expect correspondence better than 10mK between the extrapolated and the measured values.

The second way, after calibrating a PRT by comparison, and also at the gallium point, is to fit the appropriate ITS-90 equation using the data obtained by comparison, and use it to predict the resistance value at the gallium point. I find that the agreement between the predicted and the measured resistance value at the gallium point should be on the order of ± 1mK for fixed-point calibrations, or ± 3mK for comparison calibrations. If it is not, something is wrong!

(1) Isothermal Technology Ltd. Model 811 Water Triple Point Cells in Model 18233 Water Triple Point Maintenance Bath

(2) Isothermal Technology Ltd. Model 17401 Gallium Cell in Model 17402 Gallium Standard

NEW DEVELOPMENTS AND DISCOVERIES
HIGH TEMPERATURE PLATINUM RESISTANCE THERMOMETERS

by John P. Tavener

ABSTRACT

As we manufacture high-temperature platinum resistance thermometers, the process of evaluation is never-ending, and the process of learning, we can hope, is concomitant. We discover, as perhaps you will, that the high-temperature platinum resistance thermometer has idiosyncrasies, and requires attention in handling, that the old, comfortable, familiar, taken-for-granted 25.5Ω thermometer with its upper limit of 500°C or perhaps 650°C (for brief periods) had never prepared us for. Most of this is simply a function of temperature. The platinum thermometer range is now extended to 962°C, and in calibration may see temperatures as high as 1000°C, in order to achieve the silver plateau. The mechanical strength of platinum wire decreases rapidly with temperature, and also we are much closer to the recrystallization temperature. The insulating properties of insulators decline. Impermeable materials begin to exhibit at least selective permeability. Chemical activity, and crystal growth, increases much more rapidly than linearly with increased temperature.

For manufacturers and users alike (and we are both) this fastidious and demanding witch will continue to challenge us to understand, and, as we think we understand more and better, we will try to share this better understanding with our friends.

A PROBLEM - THE METALLURGICAL STATE OF THE PLATINUM COIL

Above the zinc point (420°C) the crystal structure of the platinum wire of the sensing element changes progressively with temperature. If an HTSPRT is taken out of a silver freeze plateau and into the room ambient environment, vacancies in the crystal lattice, little empty non-conducting absences in the corners, can cause an upward shift of the resistance at the water triple point of 35mK or more, and a simultaneous downward shift in \( W_{\text{gallium}} \) of about 5mK. The effect is if it were a bad strain, but it is not a strain. Fortunately, the effects of quenched-in vacancies can be removed by an annealing process, as follows:

The HTSPRT is placed in a furnace at about 650°C for an hour or more. Then the furnace temperature is ramped down at a slow rate to approximately 420°C. The rate recommended by the CCT is less than 100°C per hour [1]; experts at a Symposium hosted by CNAM in Paris recommended less than 15°C per hour [2]. When the 420°C temperature is reached, the thermometer is left to soak at that temperature for another hour, and then withdrawn into air.

We have often repeated, and will continue to repeat, our advice that proper management of an SPRT requires that after each measurement of temperature, a measurement of resistance at the water triple point be made, and these measurements conveyed to a control chart which contains the individual thermometer's complete history. Any upward shift of the water triple point resistance should be taken as requiring that the procedure of the previous paragraph be carried out. (If the shift is due to quite other causes than cycling, the original water triple point resistance may not be restored, but the primary possible cause will at least thereby be eliminated).
A PROBLEM - POISONING OF THE PLATINUM COIL

This problem is much subtler, and much more difficult to bring under control. With the familiar old 25.5 Ω thermometer used to 500°C, or 650°C, it was relatively safe to assume that if the Pyrex or quartz sheath was intact, the platinum element was safeguarded by an impermeable barrier against contamination from the outside. The safest way to regard HT-SPRTs used above 800°C is to assume that, in terms of contamination from metal ions, the quartz sheath does not exist.

When the behaviour of platinum thermometers at high temperatures was first being studied in a number of national and at least one manufacturer's laboratories, relatively similar thermometers showed startlingly different drift behaviour. Only gradually was this behaviour related to the environment surrounding the thermometer sheath; whether air, ceramic, graphite, inconel, etc. Some beautiful thermometers made by Evans at NIST, the performance of which was outstanding in the calibration laboratory where they were exposed only to the interior of quartz-and-graphite-housed freeze point cells, were wildly erratic after only brief use in the gas thermometry laboratory, where they had been inserted into inconel furnace tubes. Upon analysis, the platinum element was found to be grossly contaminated with copper and chromium. These metal ions had passed freely from the inconel through the quartz sheath, which was, at high temperatures, transparent to them.

Three approaches can help eliminate this problem:

1: The thermometer may be given a positive charge, which effectively repels the unwanted metal ions. The Isotech Model 960 Ionizer, intended for use with Model 962 thermometers and specifically tuned for each thermometer, is an excellent safeguard.

2: A sheath of platinum may be placed around the quartz sheath as a barrier.

3: A flow of air or oxygen-rich air may be maintained around the sheath to oxidize the metal ion content of any unwanted vapors. The oxide molecules are larger than their parent metal ions, and so do not seem to pass through the quartz, and, if they do, will not harm the platinum.

SOME EXAMPLES OF POISONING

1: An HTSPRT can become contaminated in the preheat tube of our Model 17702 High Temperature Furnace, at a rate of 1ppm in 15 minutes, by gases from the furnace elements (inconel and nichrome) penetrating the alumina preheat tube and then the quartz HTSPRT sheath, (if this is done without the Ionizer). AS A RESULT OF THIS RECENT DISCOVERY, WE ADVISE USERS NOT TO USE THE PREHEAT TUBE.

2: 6 HTSPRTs were contaminated by about 2ppm while they were receiving 170 hours of conditioning at 980°C. The thermometers were contained in a quartz liner inserted into an inconel heat pipe. (We had not used the Ionizer during this anneal). Gases evolved from the furnace had penetrated the quartz liner and the quartz sheath tube of the thermometer.

3: The bottom zone heater of a 3-zone furnace failed as an open circuit, causing a vertical gradient such that the platinum element was much cooler than the upper portion of the thermometer sheath. Gases from the hot end (or perhaps from outside the thermometer) condensed onto the element, causing contamination.

The effects of poisoning are recognizable as an increase in $R_{tpw}$ and a decrease in $W_{ga}$. (But note that other problems can cause similar indications).
CAN CONTAMINATION BE REMOVED?

Yes … and no.

There are two types of contamination; surface, and intermolecular. Surface contamination can generally be removed. Intermolecular contamination is rarely reversible. I have been able to remove surface contamination by passing the thermometer through a high thermal gradient - zone refining it, if you will - to drive the contaminants to a position up the stein of the thermometer, where they can reach a zone where they are harmless. I have also been able to effect improvements by using a combination of temperature, air flow and the Ionizer to “blow” contaminants out of the sheath, where they are oxidized into harmless particles. It is nevertheless inevitable that a thermometer, once contaminated, will never be as stable as one which is not.

GOOD PRACTICE - CLEAN HTSPRTS

Possibly I am causing the reader to be a bit paranoid about cleanliness of HTSPRTs, but it seems to us to be worth the precautions which may ensure the life and reliability of a thermometer. Here are some ways to keep them clean, inside and out.

1: Use clean white gloves when you handle HTSPRTs, and keep them clean.

2: Wipe down the sheath of an HTSPRT with ethylene, acetone or both, prior to taking it to temperature. This also helps preserve the integrity of the quartz. Quartz is a non-crystalline supercooled liquid which can revert to a crystalline structure (‘vitrify’) readily in the presence of a contaminant (e.g. a fingerprint) and high temperature. Vitrified quartz will leak its internal atmosphere, will weaken mechanically, and eventually disintegrate. Vitrification, once it begins, is irreversible.

3: Here are some of the precautions which can be taken when preheating a thermometer prior to placing it in a measurement situation, and we suggest that you employ all of the means (a) through (e). When calibrating the HTSPRT in an aluminium or silver cell, these precautions are unnecessary. The quartz envelope, graphite crucible, and the graphite sleeve which surrounds the thermometer sheath are adequate barriers.

(a) assure that the winding is always hotter than the lead assembly up the sheath

(b) use a quartz liner in the preheat furnace, to act as a physical barrier between the furnace and the thermometers.

(c) Bake out the preheat furnace for a long time (e.g. weeks) above the highest temperature at which you will use it, prior to preheating any HTSPRTs or inserting the liner.

(d) Have available a source of preheated air, (a small aquarium pump, plastic tubing and a long open-ended quartz tube used as a lance are ideal) Use this setup to pass air through the quartz furnace liner which contains the thermometer (in the bottom and out the top) to oxidize any metal ions present and prevent them from passing through the HTSPRT sheath. (Note: The aquarium pump should provide a consistent stream of low-velocity air, but not at such volume that it will appreciably cool the system).

(e) Use the Ionizer above 800°C, except when the thermometer is in the freezing-point cell.
If you are still concerned about contamination, use a platinum sheath around the HTSPRT sheath. (This can be so simple as a formed sheet of platinum foil). Cook out the platinum thoroughly before you introduce it to your thermometer!

Following calibration, annealing from 650°C to 420°C requires no special precautions other than those listed above.

THE CALIBRATION CYCLE AT ISOTECH

We describe here the calibration cycle used for a batch of several Model 962 HTSPRTs in the Isothermal Technology Calibration Laboratory.

1: The 962 is calibrated to obtain the resistance at the water triple point.

2: A 962 is slowly (say over a period of 1 minute) lowered into a quite separate preheating furnace, which has been stabilized at 950°C. The furnace has a closed-end quartz liner, and a flow of prewarmed air flows continually from the bottom of the liner and out the top into the room air. The Ionizer is connected.

3: Meanwhile the silver cell, contained in a Model 17702 High Temperature Furnace, has been taken through its melt to its liquid phase. A 962 is quickly transferred from the preheating furnace to the silver cell (in 10 to 15 seconds). The silver freeze plateau is established. The Ionizer is not necessary when the 962 is in the silver cell.

4: After the calibration resistance or ratio is recorded, a matter of, typically, 30 minutes, the 962 is withdrawn slowly from the silver cell (30 seconds) and placed in a clamp to cool naturally to room temperature. The clamp is arranged so that the sensing end of the thermometer is not in contact with any solid material.

5: When all of the 962s have been calibrated at the silver point, they are put into an annealing furnace at 650°C for 1 hour. At the end of that time, the furnace is allowed to cool slowly (between 14°C and 70°C per hour) to 420°C, where the thermometers dwell for another 1 hour and are then removed into room temperature.

6: The resistance is measured at the water triple point and at the gallium point.

7: The calibration at the silver point (steps 2 through 6) is repeated 3 or 4 times, and the second and subsequent results are taken to obtain the average value of \( W_{ag} \) and \( W_{ga} \). The first result is ignored, since during it, the 962 is acclimating to the depth of immersion, temperature gradient, and other characteristics of the exact experimental setup.

8: A similar procedure is used for the aluminium point, except that the thermometers are preheated at 650°C, and the ionizer is not required.

9: The zinc and tin freeze points are much simpler to do, and the technique is the same as used for the 25.5 Ω thermometers.

Dr. Marcarino [3] has suggested that, after the silver point calibration, it takes 4 hours for an HPTSPT to "acclimate" at the aluminium fixed point, but that, once acclimatized, the thermometer is reproducible. I believe that this "acclimatization" is in fact a redistribution of impurities after its excursion to the silver point, and it is possible to get repeatable results from a badly contaminated thermometer by this technique (although the thermometer may not meet the ITS-90 W-criteria). A contaminated thermometer can be recognized as one in
which the ratio at the gallium point Wga is below the ITS-90 requirement that Wga be 1.11807 or higher. Low Wga is accompanied by an irreversible upward shift of Wtpw.

**HTSPRTs IN USE IN THE CALIBRATION LABORATORY**

The ultimate purpose of an HTSPRT is in the calibration by comparison methods of other temperature sensors - e.g., thermocouples up to 962°C. The same care in use as described above is needed above 750° - 800°C. It is customary to use an inconel equalizing block in furnaces for comparison calibration. This is not recommended, because the HTSPRT will become contaminated by the inconel. We recommend that the furnace have a closed-end quartz liner, an alumina equalizing block, and an air purge to oxidize unwanted metal ions. Or, the thermometers and the air purge can be arranged in the bottom of the quartz liner, which can then be filled with alumina powder. We do not endorse the use of graphite as a shield in an inconel block, since at high temperatures the graphite will require protection by an inert atmosphere, while the HTSPRT requires to be surrounded by an oxidizing atmosphere.

It has been reported [4] that, for best results, the furnace in which the HTSPRT is used should have a gradient of 1°C or less. We can confirm this from both practical experience and theoretical considerations, but would add that if results are to be interchangeable between several laboratories, the depth of immersion must also be specified. It is good practice to assure that the furnace gradient is such that the sensitive winding of the thermometer is always warmest, to prevent impurities from condensing on it.

**A QUICK WAY TO STABILIZE AN HTSPRT**

It is normal to stabilize an HTSPRT by soaking at high temperature. However consider these two facts:

1: The thermal expansion of platinum is 9 ppm/°C, and of quartz is 0.5 ppm/°C.

2: The most stable thermometers are those where the platinum touches the quartz at the fewest number of points and where the platinum is not constrained onto the quartz surfaces.

Therefore, by dipping the thermometer into liquid nitrogen for 10 minutes, the winding reaches its minimum dimensions, and upon returning to higher temperatures is expanded away from its quartz former. Thereafter stabilization is a quicker and simpler operation with the winding loose on its supporting structure.

**ACCEPTABLE SHIFTS - REPRODUCIBILITY DURING CALIBRATION**

Table 1 shows what NPL considers limits of acceptable uncertainty for an HTSPRT during a full calibration cycle.
FINAL THOUGHTS

It can be seen from the above notes that an HTSPRT requires new thinking and new practice to those of us who are accustomed to the forgiving nature of the 25.5 Ω SPRT. Nor can I say that this is the final word. It will likely take a number of years, and a number of mistakes, until these new tools fit our hands as comfortably as the old.

During this learning process, a number of thermometers will be damaged or destroyed. It is our contention that an HTSPRT, at this stage of our understanding, must be thought of as an expendable “tool of the trade” rather than as a capital item with indefinitely long life. In general, also, HTSPRTs cannot be repaired (although I know of a world-renowned experimenter who broke four sheaths, and still uses these thermometers with new sheaths simply slipped over the internal assembly. This is not quite as daft as it sounds - an open sheath will always contain an oxidizing atmosphere, and always be at 1 atmosphere of pressure!

Once the concepts and practices described above have been understood and become practice, the users of HTSPRTs have available to them a measuring device 30 to 100 times more reproducible than the S-thermocouple it replaces. It is one of the great achievements of modern thermometry.

One last comment. Were we to take as much trouble in the use of some thermocouple combination, might we not expect stabilities approaching, within at least an order of magnitude, that of the HTSPRT? Here, surely, is an area for further research, where the results obtainable from sensitive resistance measurements can help explain e.m.f. changes in thermocouples. The key, it seems to me, lies in the separation of metallurgical changes from those caused by contamination.

FOOTNOTES

[1] Supplementary Information for the International Temperature Scale of 1990, p. 91, Bureau International des Poids et Mesures, F-92310 Sevres, France


The following Table gives the uncertainties for the calibration of platinum resistance thermometers on the International Temperature Scale of 1990, ITS-90. The uncertainties (±) are given at each of the fixed points in the various ranges between -189.3442°C and +961.78°C, and are quoted at a level of 95% confidence (±a). These are taken to vary linearly between entries in each column.

Table of Uncertainties

<table>
<thead>
<tr>
<th>Point [1]</th>
<th>Temp °C</th>
<th>Uncertainty, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range 1</td>
<td>Range 2</td>
</tr>
<tr>
<td>TP argon</td>
<td>-189.3442</td>
<td>0.002</td>
</tr>
<tr>
<td>TP mercury</td>
<td>-38.8344</td>
<td>0.0005</td>
</tr>
<tr>
<td>TP water</td>
<td>0.01</td>
<td>0.0005</td>
</tr>
<tr>
<td>MP gallium</td>
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<td>0.0005</td>
</tr>
<tr>
<td>FP indium</td>
<td>156.5985</td>
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</tr>
<tr>
<td>FP tin</td>
<td>231.928</td>
<td>0.001</td>
</tr>
<tr>
<td>FP zinc</td>
<td>419.527</td>
<td></td>
</tr>
<tr>
<td>FP aluminium</td>
<td>660.323</td>
<td>[2]</td>
</tr>
<tr>
<td>FP silver</td>
<td>961.78</td>
<td></td>
</tr>
</tbody>
</table>

[1] TP = triple point, MP = melting point, FP = freezing point.

[2] Unlike IPTS-68, ITS-90 does not provide for an extrapolation beyond the freezing point of zinc. However for most thermometers such an extrapolation is unlikely to be in error by more than 0.005°C at 500°C and 0.01°C at 600°C. NPL will generate extrapolations on this basis where appropriate and requested.

[This Table is furnished by courtesy of the National Physical Laboratory, Teddington, England, and is reproduced verbatim - the Editors]
THE CALIBRATION CYCLE FOR HTSPRTS AT ISOTHERMAL TECHNOLOGY

Key to symbols:

a = anneal for 1 hour  
p = preheat to the temperature shown  
m = measure at this temperature

Ag, Al, Zn, Sri, Ga, W3 are the equilibrium temperatures of the freezing points of silver, aluminium, zinc, tin; the melting point of gallium and the triple point of water, respectively.

Temperatures shown as "950", "650" and "420" are cell temperatures slightly below freezing equilibria, used for preheating and annealing.

Sequence A is performed 3 times in succession, and, if the results are satisfactory, the last two measurements are averaged, reported, and used in generating the interpolation table.
<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Rtpw</th>
<th>Wag</th>
<th>Ral</th>
<th>Rtn</th>
<th>Run</th>
<th>Final Rtpw</th>
<th>Wag</th>
<th>Wag</th>
<th>Rtpw shift</th>
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</thead>
<tbody>
<tr>
<td>125</td>
<td>.2523697</td>
<td></td>
<td>.852106</td>
<td>.648383</td>
<td>.477726</td>
<td>.2523695</td>
<td>1.1181595</td>
<td>4.286756</td>
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<td>126</td>
<td>.2408250</td>
<td></td>
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<td>.618724</td>
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<td>1.1181600</td>
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<td>+5.0</td>
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<td>129</td>
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<td></td>
<td>.8172365</td>
<td>.6218535</td>
<td>.4581778</td>
<td>.242044</td>
<td>1.1181600</td>
<td>4.28676</td>
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THE ISOTECH MODEL 960 IONIZER
HIGH-TEMPERATURE VAPOUR IONIZER

At high temperatures copper, iron and other metallic vapours can pass through a quartz tube as if it did not exist, and contaminate the pure metal held within the quartz.

To prevent this, Isotech has devised and patented an Ionizer. This device creates an electrical field around the tube which acts to prevent vapors penetrating the quartz.

The Ionizer is fitted into a cast aluminium box with two sockets. The green socket should be connected to Mains Earth. The black socket should be connected to the quartz tube or the metal therein.

The Ionizer should last about 5 years. To check its condition, connect a voltmeter between the green and black sockets. The voltmeter should read more than 5 volts dc. When the voltage reads below 5 volts, a new Ionizer should be purchased.

To prevent contamination, the Ionizer must be used on all occasions that the quartz tube is at high temperature, except during measurement.

Ionizers are individually tuned to the quartz tubes they are associated with, so please quote the serial number of the original Ionizer when re-ordering.

DIMENSIONS 89X35X30 MM    MAXIMUM AMBIENT 70 °C
ABOUT WORDS

AVAILABLE METROLOGY VOCABULARIES

When I use a word," Humpty Dumpty said, in a rather scornful tone, "it means just what I choose it to mean - neither more nor less.

"The question is," said Alice, "whether you can make words mean so many different things.

"The question is," said Humpty Dumpty, "which is to be master, that's all."

--Lewis Carroll, Through the Looking Glass

Happy the lexicographer who can delineate, to the satisfaction of all users of words, what those words mean, neither more nor less! In metrology, critically, it would be most agreeable if we were able to define words with the same precision as we define experiments; perhaps even state a definition of a word and its associated uncertainty!

Many standards-making agencies and organizations have found that, for the sake of accuracy and precision, and to minimize uncertainties, they must make vocabularies of the terms they use in documents. These are also useful to the writer of, for example, an article; who may then say: "I mean this term to mean what this term is defined to mean in (Reference)" Two such references, which may interest the reader, are:

INTERNATIONAL VOCABULARY OF BASIC AND GENERAL TERMS IN METROLOGY, published jointly by (and available from) BIPM (1), IEC (2), ISO (3), and OIML (4). This 35-page vocabulary defines a number of used terms under 6 section headings, "Quantities and Units", "Measurements", "Measurement Results", "Measuring Instruments", "Characteristics of Measuring Instruments" and "Measurement Standards". Any Standard promulgated by the four sponsoring organizations (and others) is required to rely upon these definitions where possible; e.g., in the implementation of the ISO 9000 series, and the EN 45000 series of EEC documents. The text is published in parallel columns in English and French. The Vocabulary is currently in revision, but at the rate of progress we note, may be for some time.

ASTM STANDARD DEFINITIONS, 7TH EDITION, published by ASTM (5). The book contains over 13,000 definitions of terms as they are used in ASTM Standards, in 560 pages. The 7th edition was published in 1990, and can be considered to be up-to-date.
While we’re at it, we might mention a little bock we have often found useful in clarifying definitions of infrequently-used units, and at other times have found pure fun. It is A DICTIONARY OF SCIENTIFIC UNITS, H. G. Jerrold and D. B. McNeill (6). Acre, Ampere, Angstrom, Bar, Barn, Bit, Bohr, Radius... OK, but how about benz, a name suggested but not generally accepted for the SI unit of velocity, ms⁻¹? or blondel (= π x lumens per square centimeter per steradian)? or clo, used (but never in Germany) in the measurement of the thermal insulation of clothing? or French degree, a measure of the hardness of water? Who would drink water in France? Not in a cron (suggested by Huxley for a time interval of 1 x 10⁶ years).

(1) Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92310 Sevres, France
(2) International Electrotechnic Commission, 3 Rue de Varembe, CH-1211 Geneva 20, Switzerland
(3) International Standards Organization, 1 Rue de Varembe, CH-1211 Geneva 20, Switzerland
(4) Organization Internationale de Metrologie Legale, 11 Rue Turgot, F-75009 Paris, France
(5) American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103 ($75 to ASTM members, $83 to the public)
HENRY E. SOSTMANN is a Consulting Metrologist practicing in temperature metrology, laboratory management and international legal metrology standards. He is a graduate of Rutgers University with graduate studies at Drew University, the Polytechnic Institute of Brooklyn, New York University and Wright State University, and is a Registered Professional Engineer. He was founder and President of H. E. Sostmann & Co, Inc., and later Vice President, Basic Metrology, of YSI. His present activities include U. S. representation an various secretariats of the International Organization for Legal Metrology (OIML) concerned with international harmonization of metrology standards.

JOHN P. TAVENER is founder and Managing Director of Isothermal Technology Ltd. (Isotech) and Thermal Developments International (TDI). He obtained his Bachelor of Science degree from the City University of London and his Master's in control theory at Cranford Institute of Advanced Technology, Bedfordshire, and is a Chartered Electrical Engineer. He worked at Rolls Royce until 1970, when he became co-founder and technical director of Sensing Devices Limited, selling his interest in SDI in 1980 to devote full time to temperature metrology.

DAVID AYRES obtained his BSc (Honors) in Physics from the University of London in 1974, followed by research at Brighton Polytechnic in co-sputtered thin films of P.T.F.E and carbon. He was employed by the Central Electricity Generating Board as First Engineer, involved with the calibration of temperature, pressure, voltage, current, power and energy devices. At CEGB, he set up a NAMAS Laboratory for temperature, pressure and voltage, using computer control techniques. In 1986, he joined Isotech as Deputy Head of Laboratory. His primary interest is in comparison calibrations. He notes that he is fond of base metal thermocouples, in particular Type N.
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