FUNDAMENTALS OF THERMOMETRY
PART V

INDUSTRIAL (USE) PLATINUM RESISTANCE THERMOMETERS

by Henry E. Sostmann, and

COMMON ERRORS IN INDUSTRIAL TEMPERATURE MEASUREMENT

by John P. Tavener

INDUSTRIAL PLATINUM RESISTANCE THERMOMETERS

ABSTRACT

The interpolation standard stipulated in the International Temperature Scale of 1990, over the temperature range from -189˚ to +962˚C, is a long-stem Standard Platinum Resistance Thermometer (SPRT); or rather, a pair of SPRTs, since no one thermometer can encompass the entire range [1]. Some characteristics required of an SPRT make it unsuitable and unfit for use outside the standardizing or calibration laboratory; therefore a variety of industrial-grade platinum resistance thermometers, of high quality, have been developed for use as field working standards, and in applications such as process monitoring and control.

DISCUSSION

The specific constrains on the SPRT, stipulated in the text of the ITS(90) [2], are that it be strain-free, that the ratio of resistances at the gallium point and the water triple point, or the mercury triple point and the water triple point, be

$$W_{ga} = R_{ga}/R_{wt} \geq 1.118\ 07 \qquad \text{Eq. 1}$$
$$W_{hg} = R_{hg}/R_{wt} \geq 0.844235 \qquad \text{Eq. 2}$$

and, in addition, if the thermometer is to be used to the silver point (962˚C), that the ratio of the silver point and the water triple point resistances be

$$W_{ag} = R_{ag}/R_{tp} \geq 4.2844 \qquad \text{Eq. 3}$$

(These constraints replace the requirement of the previous Scale, the IPTS(68), that the ratio of the resistances at 100° and at 0°C be

$$W = R_{100}/R_o \geq .0032950 \quad)$$
Eq. 4

These requirements are a well-meant but unfortunately indirect attempt to specify the purity and strain-freedom of the platinum resistance element (it is not difficult to think of a better formulation). In order to conform to this requirement, the platinum wire must be almost ideally pure, and it must be mounted on some support in a fashion which (contradictorily) provides only a minimum of support, and no constraint. Thus, while the well-designed and constructed SPRT [3] is an instrument of extraordinary sensitivity and repeatability, it is delicate, and can be easily knocked out of calibration. It has been said, correctly, that if an SPRT is put down onto a surface with enough force so that it can be heard to touch it, it may be strained out of calibration. Ironically, it may be strained due to shipping shock as it is returned from a Laboratory where it has been newly calibrated! Precautions regarding the quality assurance of SPRTs are provided throughout the literature; e.g., [4].

In addition, SPRTs are physically fragile. The best of them contain the platinum element inside a sheath of fused quartz. Quartz is an unforgiving material, in that its elastic limit and its breaking point are the same, but its use is justified by its physical tolerance of high temperatures (its softening point is about 1500°C), its available purity, its transparency, which allows the platinum element to be viewed, its impermeability to gasses (except under special circumstances) and its obvious indication that it and the construction it contains are fragile and must be treated with respect. Metallic sheaths, on the other hand, can emit vapors which are poisonous to the platinum element, and provide a spurious sense of robustness. One manufacturer provides a quartz sheath inside a metal sheath, with the net effect that the protective inside quartz can be broken by a slight bending, and the platinum element exposed to the metallic vapors, with no visible indication to the user that the system is corrupt.

"INDUSTRIAL GRADE" RESISTANCE THERMOMETERS

I have provided quotation marks around the word "Industrial" in this heading to indicate customary terminology. The use of such thermometers is by no means limited to industry, but extends into numerous other fields of science, technology, and broad common application.

Industrial resistance thermometers (IRTs) are compromise devices, where the compromise is struck between the requirement (for resistance stability) that it be as free from strain as may be compatible with use, and the requirement that it be rugged and durable in the environment for which it is intended.

It should be mentioned, briefly, that not all industrial resistance thermometers are made of platinum wire. Other constructions are:

(a) Nickel, copper, and alloy wire. Nickel and copper wire were once very popular as thermometer materials. Both have temperature coefficients of resistance higher than that of platinum; approximately 6.9 x 10^{-3} and 6.5 x 10^{-3} $\Omega/\Omega/°C$, respectively, as opposed to 3.9 x 10^{-3} $\Omega/\Omega/°C$ for platinum. This higher change of resistance with temperature reduced the burden on earlier signal amplifiers; with modern solid state electronics, the advantage is negligible. Nickel is highly non-linear and passes through a sharp change in coefficient in the vicinity of 370°C where its magnetic characteristics change. Copper has a very low specific resistance, a disadvantage for thermometry. Both materials, since they are base metals, are more susceptible to contamination and oxidation than platinum. Both cost less than platinum, but the fraction of the cost of an IPRT which represents platinum wire is small. Both have faded from popularity as resistance thermometer materials (although copper is still employed in some in-slot temperature monitors in the protective circuits for electric motors).

(b) Platinum films, thin and thick. These will be included in this discussion.

(c) Non-metallic resistance thermometers; e.g., thermistors and other semiconductors. These will be discussed in a future issue of this series.

"INDUSTRIAL" PLATINUM RESISTANCE THERMOMETERS

Thus the industrial resistance thermometer of today is likely to be an Industrial Platinum Resistance Thermometer (IPRT).

The IPRT has a longer history than its most refined relative, the SPRT. Werner von Siemens is generally acknowledged to have made the first, proposing it in his Bakerian Lecture of 1871, and advancing a three-term interpolation algorithm. It came rapidly into use, largely because of its inventor's reputation, and declined as rapidly, because of inherent problems of stability. The Siemens thermometer comprised 1

meter of 0.1 mm (0.004 inch) diameter platinum wire wound on a porcelain or fire-clay tube, the whole assembly enclosed in an iron tube for protection. (Siemens also experimented with sensing elements of ceramic impregnated with platinum group metals).

A committee of the British Association for the Advancement of Science found that the resistance of the Siemens thermometer increased upon each heating, making it necessary to calibrate the thermometer each time it was used (and a calibration is a use). The change in resistance, reported to reach 15% after repeated heatings to 900°C, was assigned to chemical alteration in the platinum. (Two probable other reasons for increase in resistance are (a) gradual volatilization of some platinum, resulting in a decrease in sectional area of the wire, and (b) the growth of intergranular boundaries, affecting the conduction mechanism at these points).

About 20 years later, Callendar, and Callendar and Griffiths, revived the platinum thermometer for laboratory use over moderate temperature ranges. Callendar found that the clay substrate was a major cause of the variation of resistance; that the platinum wire "became brittle and stuck to the clay". We can guess now at gross silica contamination. On the other hand, a mica strip, that the platinum touched only at the edges, appeared to be "perfect" insulation in that it did not cause contamination. Callendar also stipulated that all joints with platinum be autogenous fusion weldments without foreign material such as solders; that pressure joints (screws or torsion) be avoided, and that copper conductors in the heated zone be eschewed, because of the volatility of the material; and we observe these strictures today.

As a generality, the work of Callendar and Griffiths was confined to the range 0° to 550°C. Over this range, they found that a third-order parabolic equation using three fixed points, ice, steam, and the boiling point of sulfur, was adequate to establish an interpolation scheme. Of the famous Callendar equation, which was the basis for International temperature Scales until 1968, more later.

PLATINUM AS A THERMALLY SENSITIVE MATERIAL

The development of the platinum resistance thermometer paralleled, in time, the development of platinum itself as a workable and pure material. Callendar's platinum was certainly not equivalent to pure platinum and the SPRT as we think of it today.

Platinum, as first refined, occurs as a spongy mass. In the mid years of the 19th century, it was beyond technology to force this mass

into an ingot by methods which retained its purity, and the wrought metal was obtained, essentially, by hammering. Today, it can be melted into an ingot which is then further compacted by successive swagings and annealings, until it is finally in the form of a square-sectioned bar ready to roll into strip, and eventually to draw into wire. Modern techniques for managing platinum, from the sponge to wrought wire, are generally proprietary [5].

A CONFUSION OF INDUSTRIAL STANDARDS

A corollary of the improvement in metallurgical techniques is increase in the temperature coefficient of resistance exhibited by the wire. The purer the material, the higher the temperature coefficient. Let us recall that most useful coefficient, a, a regrettable victim of the IPTS(68) and its subsequent replacement Scales:

$$a = R100/R0 \qquad\qquad \text{Eq. 5}$$

a is, therefore, the measure of the sensitivity of platinum wire stated as the slope of a straight line between 0°C and 100°C, and is expected to remain a useful and popular way of classifying IPRTs.

For platinum of purity approaching ideal, a is higher than 3.928 x 10^{-3} Ω/Ω/°C (assuming always the absence of strain). The best of production SPRTs today have a coefficients between 3.925 x 10^{-3} (the minimum a permitted on the IPTS-68) and 3.928 x 10^{-3}.

Industrial resistance thermometry has a much longer history of use in Europe than it has in the United States. I cannot trace this history, but certainly resistance thermometers were commonplace in measurement and control early in the 20th century. This period predates the preparation of modern platinum, and, in consequence, the European standard for a has been fixed, before recent memory, at 3.850 x 10^{-3}; quite probably, the best, but hardly ideal, wire that could then be obtained.

The migration of European process engineers to the United States after the war turned Western Hemisphere attention to IPRTs as more precise devices than process thermocouples. In the mid-1950s, I made 400 process-control IPRTs for a duPont textile fiber plant; the largest order ever placed, at that time, in the U. S. I made these from the best Cohn wire, and achieved a coefficients of about 3.916 x 10^{-3}. Obviously, these elements were not strain free; a compromise was necessary in order that they be stable under conditions of industrial use.

In the absence of an American standard for a, 3.915 x 10^{-3} became the *de facto* U. S. standard, while the European standard, cast in concrete, remained 3.850 x 10^{-3}. The American *de facto* standard reflected pure platinum wire in a less than ideal physical structure, while the European coefficient, once derived from platinum wire less than ideally pure, now reflected pure platinum wire doped with specific impurities [6]. The situation of two (and there were more than two) accepted coefficients would obviously cause problems. For example, a controller scaled for one coefficient would indicate (except at 0°C) improperly if the sensor were of the other coefficient. Many unsuccessful attempts at compromise were made, by many standards-writing bodies. SAMA, for example, promulgated a standard in which the sensing element a was required to be 3.923 x 10^{-3} (a completely unrealistic number for an IPRT) and was then shunted with prescribed shunts to an effective coefficient of either 3.915 x 10^{-3} or 3.850 x 10^{-3} (which incidentally altered the shape of the characteristic curve). The response of U. S. manufacturers to the confused situation was to produce sensors of both coefficients.

SPRTs are considered by their users to be individual instruments, whose characteristics are completely and adequately described by individual calibration constants and printed interpolation tables. IPRTs, however, are specified not as individual sensors, but as members of a group performing within certain limits. The primary emphasis here is on the interchangeability of like sensors, so that field replacements may be made without the necessity of recalibrating systems or processes. Elements may be checked by the manufacturer on an individual or on a statistical basis, and, often, the difference between thermometers of several accuracy classes represents sorting at inspection. An individual calibration of such a sensor is almost never done except in batch qualification, and is never offered to the user except as an extra-cost option.

It seems today that the confusion will eventually be resolved, not on technical grounds, but by demands of the marketplace for harmonization of standards on a global basis. A task group of the International Electrotechnic Commission (IEC) is formulating a revision of the IEC document on industrial resistance thermometers, and it will be based on the European a coefficient only. The IEC standard will be adopted rapidly and verbatim into the European Community standards documentation, as a DIN, BSA, etc. National standard, and the need to comply will be persuasive to all manufacturers, including those in the United States who wish to export.

In the absence of a uniform standard at this time, we offer Table 1, which lists tolerances and coefficients for IPRTs promulgated as National regulations within IPTS(68). (Note that the tolerances shown in

TABLE 1

INTERNATIONALLY AGREED UPON SPECIFICATIONS (PRIOR TO ITS-90)

	IEC PUB 751 1983	OIML 1985	BS 1904:1984	DIN 43760	GOST 6651-84	JEMIMA	SAMA RC4(1966)
R(0 DEG C) OHMS	100	5 to 1000	100	100	10, 46, 100	100	100
TOLERANCE AT 0							
CLASS A	+/-0.06						
CLASS B	+/-0.12		+/-0.075	+/-0.06	+/-0.15	0.03 appr	special
			+/-0.1	+/-0.12	+/-0.3	0.5 appr	standard
ALPHA	0.00385	0.00385	0.00385	0.00385	0.00385	0.003916	0.003923
		0.00391			0.00391		
TOLERANCE							
CLASS A	+/-1.3E-05	+/-0.7E-0.5	+/-0.7E-05	+/-1.3E-05	+/-0.7E-05		
CLASS B	+/-3.0E-05	+/-1.2E-05	+/-2.0E-05	+/-3.0E-05	+/-1.1E-05		
RANGES, DEG C							
CLASS A	-200 TO 650		-183 TO 630		-200 TO 600	-200 TO 600	-200 TO 600
CLASS B	-200 TO 850	-200 TO 850	-220 TO 1050	-200 TO 850	-200 TO 850		
COEFF TYPE I							
A	3.90802E-03	3.90802E-03	3.96835E-03	3.90802E-03	3.90802E-03	3.97478E-03	3.98153E-03
B	-5.802E-07	-5.802E-07	-5.8349E-07	-5.80195E-07	-5.802E-07	-5.8775E-07	-5.8531E-07
C	-4.2375E-12	-4.274E-12	-4.3557E-12	-4.2735E-12	-4.2735E-12	-3.4813E-12	-4.3545E-12
COEFF TYPE II							
A		3.96968E-03			3.96847E-03		
B		-5.8677E-07			-5.847E-07		
		-4.141E-12			-4.3558E-12		

NOTE: IEC = INTERNATIONAL ELECTROTECHNIC COMMISSION; OIML = INTERNATIONAL ORGANIZATION FOR LEGAL METROLOGY; BS = BRITISH STANDARD; DIN = DEUTSCHE INSTITUT FUER NORMUNG; GOST = GOSSTANDARD (ALL-UNION STANDARD, USSR); JEMIMA = JAPANESE STANDARD; SAMA = SCIENTIFIC APPARTUS MAKERS ASSOCIATION (UNITED STATES)

FIGURE 1

INDUSTRIAL RESISTANCE THERMOMETER TOLERANCES SPECIFIED BY
IEC IN 1983   CLASS A   CLASS B

Table 1 are at 0°C. Fig. 1 shows the IEC 1983 tolerances at other temperatures). The Table suggests that almost any single international standard will be welcome, in place of these many conflicting standards.

A Table of values of resistance versus temperature may be calculated from any of these using the following algorithms (stipulated in the standards), which closely resemble the formulations of Callendar (above 0°C) and Callendar-Van Dusen (below 0°C). (In these equations, A, B and C are equivalent to but not numerically the same as Callendar-Van Dusen's α, δ and β).

Above 0°C:

$$R(t) = 1 + At + Bt^2 \qquad\qquad \text{Eq. 6}$$

Below 0°C:

$$R(t) = 1 + At + Bt^2 + C(t - 100)t^3 \qquad\qquad \text{Eq. 7}$$

Tables calculated using these equations will not be identically in accord with IPTS(68), since these equations represent mathematically continuous functions, and the IPTS(68) interpolation equations do not. (Think of the IPTS(68), and also the ITS(90), as a long clothesline hung between two supports, in a catenary curve, but interrupted at intermediate points by the fixed points which enter into the equation, giving the curvature of a clothesline supported by intermediate props). However it is stated by the designers of IPRT standards that the differences are not "industrially significant". (The major difference from IPTS(68) was about 15 mK plus the difference of the individual thermometer from the nominal curve). Until we have seen the equivalent constructions for ITS(90), it is not possible to estimate the divergence between the industrial scale and the ITS(90). Our prediction is that it will be much larger, because of the nature of the ITS(90) algorithms. Perhaps what we need (I appreciate what heresy I speak) is a quite distinct Industrial Platinum Resistance Thermometer Scale; an International Practical Temperature Scale.

THE CONSTRUCTION OF IPRT SENSING ELEMENTS

Most manufacturers of IPRTs do not stint on the quality of the platinum wire used for the sensing element, but commonly purchase "reference grade" wire when the α coefficient is to be 3.92 x 10^{-3} or higher, and the best wire when α is to be 3.85 x 10^{-2}. Lead wires may be commercial grade platinum. Occasionally other materials than platinum are used for lead wires, but platinum is preferable because it avoids ac-

cidental thermoelectric junctions in the hot zone of the finished thermometer.

The resistance at 0˙C may be 100Ω, 200Ω, 500Ω or some other value. For the 100Ω element a typical wire diameter is 0.025 mm (0.001 inch) for the realistic reason that this is the diameter at which the sum of the cost of the platinum metal and the cost of drawing the wire is a minimum. Higher 0˙C resistance elements may employ even smaller diameter wire, 0.015 mm (0.0006 inch) being a realistic lower limit imposed by physical handleability. The wire is usually supplied in the hard-drawn condition to avoid stretching it during manufacture.

There have been a number of schemes for the disposition of the platinum wire upon the supporting structure. All are contrived to provide some freedom for the wire to expand, contract, etc., with minimum induction of mechanical strain, while still restraining the wire so that the physical motion of the wire as an accelerated mass will not in itself induce strain, or in the extreme example, cause unwanted turn-to-turn contact.

A design I used for many years is as follows. .001 inch diameter wire, coated with a film of Isonel varnish 0.0001 inch thick, was wound onto a high-purity alumina mandrel, and the ends spot welded to platinum lead wires fixed within the mandrel. After trimming to resistance tolerance, the system was dip-coated with ceramic, dried, and fired to anneal and to vaporize and drive off the varnish. (In later production, the winding was surrounded by a loose-fitting ceramic tube, and the interspace filled with ceramic powder compacted centrifugally). This left the wire free in a helical tunnel perhaps 0.0002 inch larger than the wire diameter. Since the thermal expansion of platinum is higher than that of the ceramic mandrel, it was necessary, first to stretch the wire by several cycles from room temperature to liquid nitrogen temperature, and then to re-anneal the wire above its upper temperature of use.

FIGURE 2

Alumina core ⎯
Packed powder ⎯
wire in tunnel ⎯
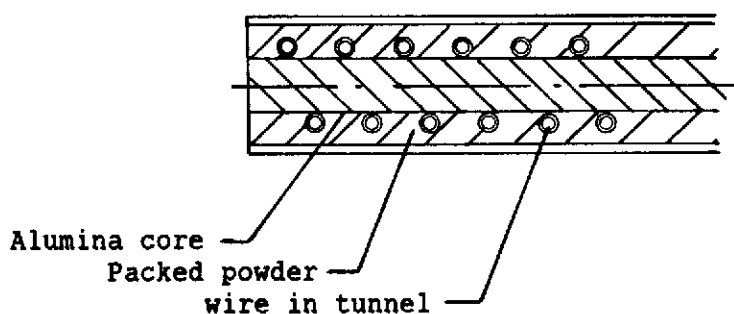
The "tunnel" construction of an element

In an experiment to determine the effectiveness of this construction, a large number of thermometers (ca 100) were made using bare wire, which would be closely captured by the coating, and Isonel-coated wire, which could be expected to have the freedom described above. All other details were common to both sets. The close-captured thermometers exhibited an a coefficient closely grouped about the mean of 3.915×10^{-3}, while the loosely-retained thermometers were all about 3.920^{-3}. Obviously, the latter were freer from strain. Fig. 2 indicates the tunnel construction.

The most usual design, due to Curtis and other workers, is to prepare two fine-diameter coils of platinum wire, and place these within two bores of a four-bore ceramic insulator, the other two bores being used to capture lead wires. The coils are welded together at one end and to the lead wires at the other end. A cement, ceramic or glass-based is introduced into the tubes holding the coils, in such manner that the cement contacts and secures only some specific portion of each turn. Fig. 3 indicates this construction.

FIGURE 3

Ceramic tube
Platinum coil
Line of cement
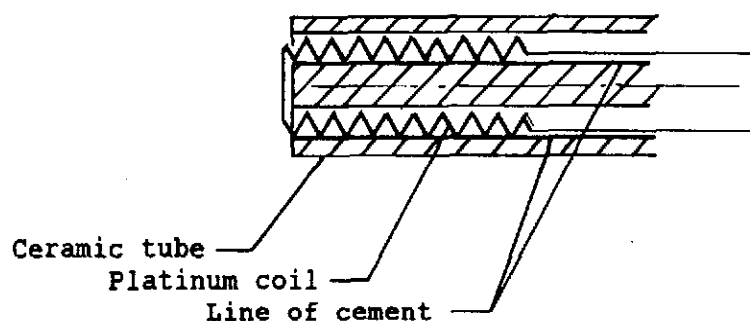
The "2-coil" construction of an element

Stability with temperature change, and stability with mechanical shock and vibration, are directly contradictory requirements, and one many be satisfied only at the expense of the other. In the construction described above, the manufacturer has a wide range of choice between sticking down only a very small fraction of each turn of wire, for best thermal stability, a very large fraction (or all) of each turn for best mechanical stability, or any desired compromise between these.

These basic designs have been in use for many years. This is not to say that there has been no improvement over these years. The modern IPRT is superior for the following reasons, among others:

a: The fine platinum wire employed is now drawn through laser-drilled sapphire or diamond dies, which give repeatable results without contaminating the platinum.

b: Ceramic materials, mandrels, substrata and cements, have reached a development stage of purity undreamed of even 10 years ago.

c: Techniques have been developed which permit sensing elements to be thin and long, short and fat, very small, flat and rectangular, to include two or more electrically separate matched elements, etc. Examples of available shapes and sizes are shown in Table 2 [7].

FILM ELEMENTS

Much work has been done to develop platinum sensors based on thin- and thick-film technology, but the results have been to date disappointing. The hoped for results of lower cost and performance equivalent to that of wrought-wire sensors have simply not been realized, and there is now reason to doubt that they can be.

(a) Film thermometers must be mounted intimately to a substrate, but a substrate material of identical mechanical expansion properties has not yet been identified. Many film elements are excellent thermal expansion strain gages!

(b) The paste or film, which contains very little metal, is easily contaminated, and therefore usually is sealed under a glassy coating, which is subject to the problems of (a) and also may contaminate the platinum.
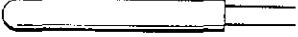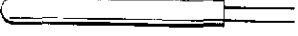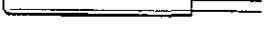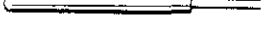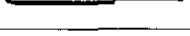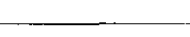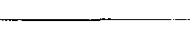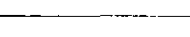
(c) The inhomogeneity of the paste provides characteristics entirely different from wrought wire; resembling, rather, spongy platinum.

(d) Characteristics vary from batch to batch, as a function of sintering temperature, etc.

(e) The thin film units are so small that self-heat is a problem not solved.

(f) mechanical attachments of leads, etc., are weak and susceptible to the generation of thermal emfs.

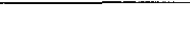| All dimensions in mm Detectors shown same size	Resistance tolerance at 0°C	Ceramic length	Ceramic diameter	Sensing length
P100/7040	0,1%	70mm	4mm	65mm

P100/5024
P2100/5024
	0,1%	50 + 0
		   − 0,5
			2,4 + 0
			   − 0,03
				47 ± 1

P100/5015
P2100/5015
	0,1%	50 + 0
		   − 0,5
			1,5 + 0
			   − 0,03
				48 ± 1

P100/3045
P2100/3045
	0,1%	30 + 0
		   − 0,5
			4,5 + 0
			   − 0,03
				27 ± 1

P100/3038
P2100/3038
	0,1%	30 + 0
		   − 0,5
			3,8 + 0
			   − 0,03
				28 ± 1

P100/2532
P2100/2532
	0,1%	25 + 0
		   − 0,5
			3,2 + 0
			   − 0,03
				22 ± 1

P100/2528
P2100/2528
	0,1%	25 + 0
		   − 0,5
			2,8 + 0
			   − 0,03
				22 ± 1

P100/2524
P2100/2524
	0,1%	25 + 0
		   − 0,5
			2,4 + 0
			   − 0,03
				22 ± 1

P100/2515
P2100/2515
	0,1%	25 + 0
		   − 0,5
			1,5 + 0
			   − 0,03
				22 ± 1

P100/2516
P2100/2516
	0,1%	25 + 0
		   − 0,5
			1,6 + 0
			   − 0,03
				22 ± 1

P100/2020
P2100/2020
	0,1%	20 + 0
		   − 0,5
			2,0 + 0
			   − 0,03
				17 ± 1

P100/1545
P2100/1545
	0,1%	15 + 0
		   − 0,5
			4,5 + 0
			   − 0,03
				12 ± 1

P100/1532
P2100/1532
	0,1%	15 + 0
		   − 0,5
			3,2 + 0
			   − 0,03
				12 ± 1

P100/1528
P2100/1528
	0,1%	15 + 0
		   − 0,5
			2,8 + 0
			   − 0,03
				12 ± 1

P100/1524
P2100/1524
	0,1%	15 + 0
		   − 0,5
			2,4 + 0
			   − 0,03
				12 ± 1

P100/1520
P2100/1520
	0,1%	15 + 0
		   − 0,5
			2,0 + 0
			   − 0,03
				12 ± 1

P100/1516
P2100/1516
	0,1%	15 + 0
		   − 0,5
			1,6 + 0
			   − 0,03
				12 ± 1

P100/1515
P2100/1515
	0,1%	15 + 0
		   − 0,5
			1,5 + 0
			   − 0,03
				12 ± 1

P100/1512	0,1%	15 + 0 − 0,5	1,2 ± 5%	12 ± 1
P100/1509	0,1%	15 + 0 − 0,5	0,9 ± 5%	12 ± 1

P100/1012	0,1%	10 + 0
		   − 0,5
			1,2 ± 5%	8 + 0
				   − 1

Nevertheless film sensors seem adaptable to uses which require no great accuracy or stability, and where cost is a paramount consideration; e.g., home heating and air conditioning systems.

HOUSING THE IPRT SENSOR

Almost all IPRT sensors require some sort of enclosure when they are put to use, to protect the sensor, provide for the securing of external connecting wires, close off the spaces into which they are inserted, couple them to a process or an environment, etc. The variety is limited only by the configuration of the sensor chosen, and the ingenuity of the designer.

For those who need only one or a few special configurations, it is not excessively difficult to buy sensors and assemble thermometers on a do-it-one's-self basis. Precautions include the necessity to preserve cleanliness, to make impeccable joinings of wires, to pay attention to thermal coupling between the sensor and the outside environment, and to provide adequate electrical isolation. For those who require more than a few thermometers, it is usually more effective to adapt to the many commercial configurations available, or to seek an assembler willing to make up special configurations. It is possible to mount IPRT sensors in tubes, wells, drilled holes in casings, machine screws, etc.

CALIBRATING THE IPRT

Accurate calibration of an SPRT, in at least one sense, is simple compared to calibrating an IPRT. One has only to have a suitable set of fixed points into which an SPRT fits, diametrally and with sufficient immersion, and the rest is straightforward.

The majority of IPRTs cannot be calibrated in the usual sort of ITS(90) fixed point cell, because they won't fit, or they are not designed for sufficient immersion, or because they won't tolerate the temperatures along the length of the lead wires.

The concept of the "Like Standard" is a useful one in the calibration of IPRTs. It comprises the creation of a reference thermometer, as "like" as possible to the thermometer to be calibrated, but altered in whatever manner is necessary to adapt it to a fixed point cell.

An example is shown in Fig. 4. This small sheathed thermometer is intended to be screwed into the hot zone of a spinnerette for making a textile fiber. In use, the tip projects into a stream of high-velocity steam. Since the leads are external to the heated system, they are Tel-

fon insulated. The hexagonal nut is too large to fit a fixed-point cell, and the leads will not tolerate the temperature.

A "like standard" was made by (a) reducing the diameter of the hex nut and the threaded portion (b) substituting glass-insulated leads for the Teflon leads of the working thermometers. It was then possible to obtain calibrations of the "like standard" at fixed points , so that the "like standard" could serve as a reference thermometer for comparison calibrations of the working thermometers.

FIGURE 4

Teflon leads —

The test object

The hex removed —
fiberglas leads —
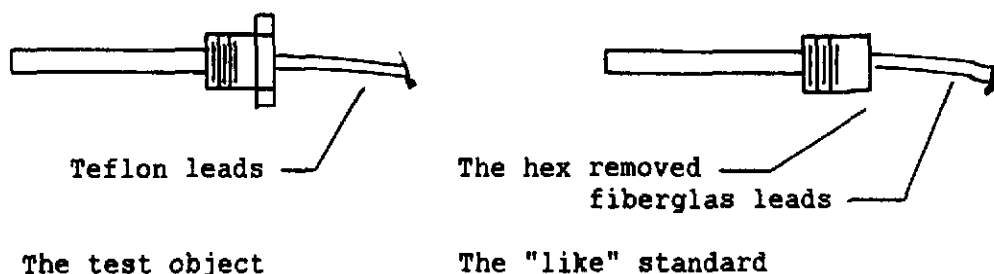
The "like" standard

The short length of the thermometer meant that the immersion depth would not be sufficient. The paper by John Tavener which immediately follows will suggest the errors inherent in the system. However the "like standard" had, intentionally, the identical deficiencies, and when the standard and a working thermometer were screwed side-by-side into a copper block, and the block immersed in a constant-temperature bath, these deficiencies cancelled almost exactly.

One might well ask: but in use, did the working thermometer accurately realize the temperature of the steam? In this real-world example, no one really cared. The relevant matters were (a) once the process had been optimized, the working thermometer maintained the preset temperature (b) any replacement of the working thermometer (say in the event of its failure) had the same calibration and characteristics.

COMMON ERRORS IN TEMPERATURE MEASUREMENT

ABSTRACT - JOHN P. TAVENER

It is the first law of thermometry that a thermometer senses no temperature except its own. While it is easy to obtain steady readings of temperature from a resistance thermometer, it is much more difficult to be sure that these readings indicate the temperature of the object or environment of interest.

Of the almost infinite number of ways in which errors can occur, some of the more obvious are discussed here, together with an estimate of the magnitude, and corrective measures which may be applied.

INTRODUCTION

If two systems in thermal equilibrium are each the same temperature as a third, then they are also the same temperature as each other. But no perfect system exists. The temperature of an object is affected by the thermometer, and the thermometer may be temporarily or permanently affected by the system into which the thermometer is immersed.

In obtaining a steady reading with a thermometer, the following need to be considered, before one can accept the reading as the correct system temperature.

1: Thermal lag; the delay caused by the thermometer's thermal or electrical inertia

2: The thermometer's thermal capacity

3: Immersion error, caused by heat transfer from the system (including the environment) to the thermometer

4: Self-heating, caused by the necessity of passing a current through the thermometer

5: DC errors; effects of emfs caused by junctions between dissimilar metals

6: Effects of lead resistance

1: Thermal lag. If a small-diameter thermometer is inserted loosely into a large diameter pocket or well, one feels instinctively that the thermometer immersion should be deeper than if it were a tight fit, or the pocket or well were absent. Not necessarily true: the size of an air gap around the thermometer is almost irrelevant, compared to the fact that there *is* an air gap.

(I once had the problem of designing a thermometer for a reactor bypass cooling water loop, which had to show a 63% response time of 2 seconds in water flowing turbulently at 2000 feet per minute at 3000 psig, so that the fast response had to be achieved in a mechanically very rugged construction. The sensing element was mounted in a hole drilled in a taper pin, and embedded in a beryllium oxide paste. The

interior of the sheath was reamed to hold the taper pin. The response time was 8 times longer with the pin loosely in place than when it was driven tight, as a result of the very slight air gap! - HES)

However the combination of thermal resistivity between the thermometer and the temperature to be measured, and the heat capacity of the thermometer itself, give rise to an effect known as thermal lag. The heat flow required to warm or cool the thermometer causes a finite response time. I describe this effect with an electrical model in Fig. 5:

FIGURE 5
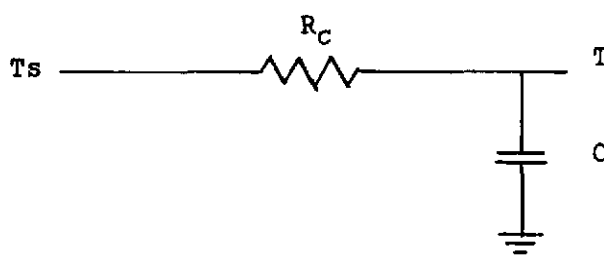
An electrical analogue model of thermal lag

Fig 5: Thermal lag. T_i = the initial temperature of the thermometer, T_s and T are the temperatures of the system and the thermometer respectively, R_c is the thermal resistance between the thermometer and the system, C is the heat capacity of the thermometer, and τ is time to achieve a 63% response.

Then the error in the temperature measurement (the shaded area of Fig. 6) is

$$T_e = -(T_s - T_i) \exp(-\tau/T) \qquad \text{Eq. 1}$$

Other ways of expressing time constant are commonly found in the literature, and there appears to be no general consensus on how to present this information. Usually, however, a manufacturer specifies how the information he provides was determined.

In a practical situation, the user can make the error arbitrarily small by waiting for a sufficient time. Fig. 6 shows the factor

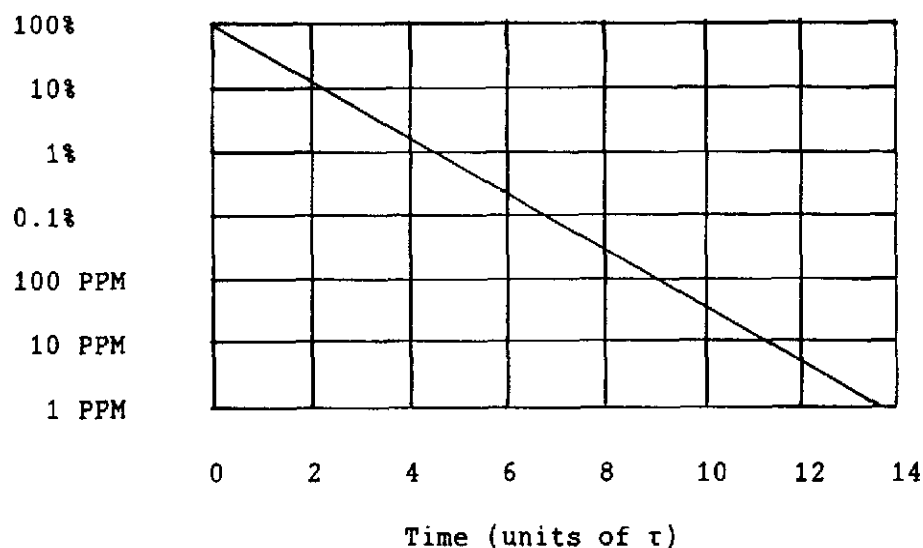$$T^e/(T_s - T_i) = -\exp(-\tau/T) \qquad \text{Eq. 2}$$

in multiples of the response time.

FIGURE 6
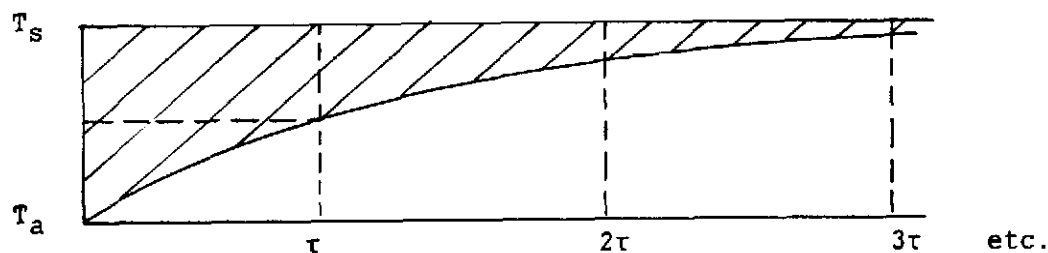
The effect of thermometer response time on a measurement

FIGURE 7

Time (units of τ)

Temperature error $T_e/(T_s - T_i)$ plotted against measurement time in multiples of τ

EXAMPLE: Estimate the minimum measuring time to achieve an accuracy of better than 0.1% when measuring a temperature near 150°C with a thermometer whose response time is 15 seconds.

The maximum error is
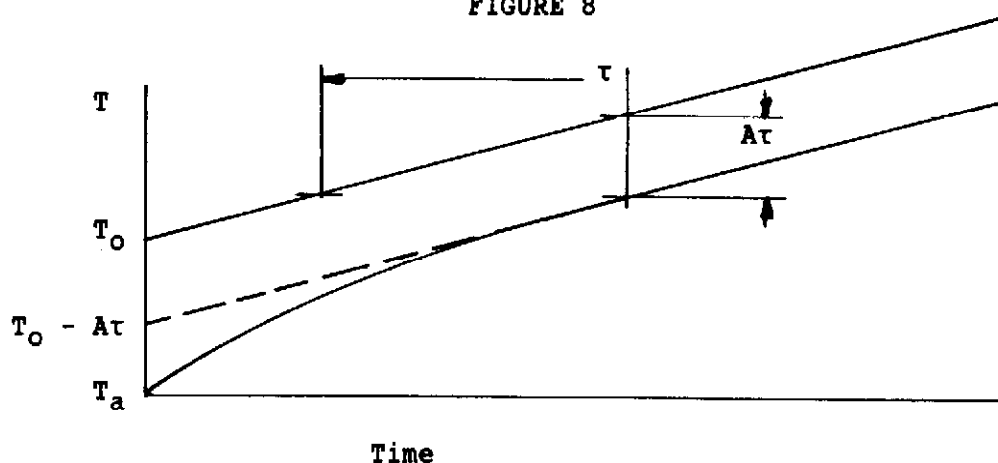
$$0.1°C/(150° - 20°) = 0.07\%$$ Eq. 3

From Fig. 7, the minimum measurement time is $7\tau = 105$ sec.

In systems where the temperature is not constant, the measurement errors become more complex. Consider the situation in which the

FIGURE 8

Temperature error due to the thermometer time constant
in a system with the system temperature constantly rising

In systems where the temperature is not constant, the measurement errors become more complex. Consider the situation in which the system temperature rises continually, as in Fig. 8. Here there are two error components, an exponential component

$$T_{e1} = -(T_o - AT - T_i) \exp (-\tau/T) \qquad \text{Eq. 4}$$

and a constant component

$$T_{e2} = -AT \qquad \text{Eq. 5}$$

where the system temperature $T_s = T_o + A_\tau$ and A is the rate of rise of the system temperature.

The exponential component, T_{e1}, can be dealt with by waiting for a long enough time. The constant component T_{e2} can be dealt with only by using a thermometer of shorter time constant.

2: Thermal capacity. When a thermometer is immersed into a system, heat will flow between the system and the thermometer until equilibrium is reached. Unless the system temperature is under external control, a permanent change in the system temperature will result. The smaller the heat capacity of the thermometer, the smaller will be the effect upon the system temperature. A simple model of the measurement process provides an estimate of the resultant temperature error:

Let C_t and C_s be the heat capacities of the thermometer and the system respectively, T_s be the final system temperature, and T_i and T_f be the initial and final temperatures of the thermometer. Then

$$T_e = -[C_t/(C_s + C_t)][T_s - T_i]$$ Eq. 6

and rearranging,

$$T_e/(T_s - T_i) = C_t/(C_s + C_t)$$ Eq. 7

Therefore, to achieve less than 1% error, the heat capacity of the thermometer C_t should be at least 100 times smaller than the heat capacity of the system C_s.

EXAMPLE: Suppose a thermometer has a heat capacity of $5J^{\cdot}C^{-1}$, and is used to measure the temperature of a cup of coffee. Estimate the temperature error due to heat capacity. Assume that the temperature of the coffee is $80^{\cdot}C$, the initial temperature of the thermometer is $20^{\cdot}C$, and the heat capacity of coffee = the heat capacity of 250 ml of water = $1000J^{\cdot}C^{-1}$.

From Eq. 5,

$$T_e = [5J^{\cdot}C^{-1}/1000J^{\cdot}C^{-1}][80^{\cdot}C - 20^{\cdot}C] = 0.3^{\cdot}C$$ Eq. 8

The thermometer used in this Example is a small sheathed IPRT. Small thermistors and very fine thermocouples can have heat capacities less than $0.02J^{\cdot}C^{-1}$, while mercury-in-glass thermometers may have heat capacities of as much as $200J^{\cdot}C^{-1}$. Such a mercury-in-glass thermometer would show a $12^{\cdot}C$ error; even in 30 liters of coffee, the error would be $0.1^{\cdot}C$.

In many measurements, it is possible to preheat or precool the thermometer, so that the initial temperature of the thermometer is close to the system temperature.

3: Thermometer immersion depth. A definition: A thermometer is sufficiently immersed in a system when there is zero heat flow between the sensor and the external non-system environment through the leads, sheath or other thermometer parts that extend from the sensor to ambient temperature.

Heat flowing through the thermometer from or to ambient is absorbed or replaced by the system in the forms of conduction, convection and radiation. A simple model:

$$\delta T = qR \qquad\qquad\qquad \text{Eq. 9}$$

where δT = temperature difference, q = heat flow and R = thermal resistance. This can be compared to Ohm's Law, and represented shown in Fig. 9:

FIGURE 9

Contact resistance   T   Leakage Resistance

System Temperature   Therm Temp   Ambient Temperature
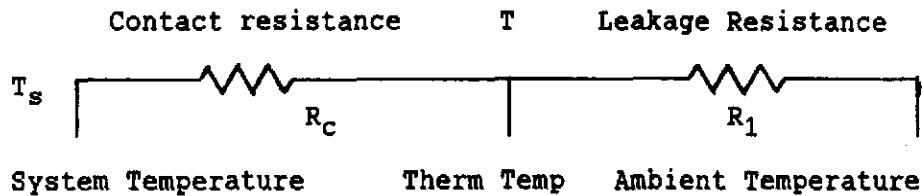
a: The greater the immersion depth, the greater the resistance to leakage; therefore the thermometer should be immersed as far as may be practicable.

b: The greater the immersion depth, the smaller the contact resistance is likely to be.

c: The contact resistance also depends upon the thermal conductivity of the system, if a fluid how fast the fluid is flowing, whether the flow is laminar or turbulent, and whether there is cavitation behind the thermometer.

A simple formula is:

$$T_e = (T_a - T_s)\, K_o \exp(-L/Lo)$$
Eq. 10

where T_e = temperature error, T_s = system temperature, L = immersion length of the thermometer, L_o a constant called the "characteristic length of the thermometer", T_a = ambient temperature, and K_o = a constant always less than 1.

In instances where the conductivity of the system is poor, or where high precision is required, a simple experiment will determine L_o and estimate the magnitude of T_e. At least three measurements must be made. at immersion depths of L_1, L_2 and L_3 = δL. Temperatures of T_1, T_2 and T_3 are obtained.

$$Ts = T1 + [T_2 - T_1]^2/[2(T_2 - T_1) - (T_3 - T_1)] \qquad\qquad \text{Eq. 11}$$

and, rearranging Eq. 10,

$$L_o = [\delta L]/\ell n[(T_s - T_1)/(T_s - T_2)] \qquad \text{Eq. 12}$$

EXAMPLE: Suppose that measurements at immersion depths of 3, 4 and 5 cm give measured temperatures of 115°, 119° and 121°C. What is the system temperature and the characteristic length of the thermometer?

$$T_s = [119 - 115]^2/[2(119 - 115) - (121 - 115)] \qquad \text{Eq. 13}$$
$$= 123°C$$

$$L_o = [4cm - 3cm]/\ell n[(123 - 115)/(123 - 119)] = 1.44 \text{ cm} \qquad \text{Eq. 14}$$

4: Self-heating error. A resistance thermometer is a passive electrical element; in order to make a measurement of its resistance, a current must be passed through it. This inevitably results in some heating of the thermometer, which is inevitable:

$$P = I^2 R \qquad \text{Eq. 15}$$

This results in an elevation of the apparent temperature of the thermometer (which measures only its own temperature) and an elevation of the system temperature. The problem is to evaluate whether this heating is significant in terms of the accuracy required of the measurement.

The self-heating effect is readily determined by placing the thermometer in a controlled environment and making measurements at at least two impressed currents. From this the so-called "zero power resistance"; that resistance which would be measured if it could be measured with no impressed power; and the actual resistance measured at any current may be estimated as a difference from R_o:

$$R_o = [R_1 - i_1{}^2][(R_2 - R_1)/(i_2{}^2 - i_1{}^2)] \qquad \text{Eq. 16}$$

5: Voltage errors. Most resistance-measuring systems compare the voltage across the unknown resistor with that across a reference resistor. Therefore any extraneous voltages which arise in the measurement path are a source of error.

The largest DC error is caused by imperfect amplifiers. The ideal amplifier develops zero voltage when both inputs are at zero potential. Any output voltage which occurs under these conditions can be replaced by an equivalent DC input voltage V_{os}, referred to as the input offset voltage of the amplifier. Most manufacturers of amplifiers supply data

sheets giving a typical or maximum value for V_{os}, which may typically range from 20 µV to 5 mV depending upon the type or quality of the amplifier. The offset voltage and its sensitivity to various parameters (e.g., temperature, power, supply voltage and time) represent the most important sources of error in operational amplifier circuits.

Thermal emfs are another important type of DC error. They are generated when junctions of leads of dissimilar materials act as thermocouple junctions. (Even joints in copper wire from two different manufacturers may produce emfs as high as 0.2 $\mu V^{\cdot}C^{-1}$. The emf of a copper-platinum junction is typically 6 to 8 $\mu V^{\cdot}C^{-1}$.

In assembling a thermometer, the maker should avoid making lead junctions from different types of wire, especially wire that may have become contaminated. The net emf can be further reduced by keeping pairs of junctions close to each other (i.e., at the same temperature), and, if solders are used at all, employing "low thermal" solders.

Voltaic emfs arise from electrochemical activity between dissimilar metals, in the same way that batteries generate voltage. The problem should not occur if the same wire is used throughout, the joints are perfect, and the environment is clean and dry.

Temperature error caused by DC voltage errors is given by

$$T_e = V_e/S \hspace{5cm} \text{Eq. 17}$$

where V_e is the input voltage error (mV) and S is the sensitivity of the instrument (mVC^{-1}).

Although it is possible to reduce some of these errors by good technique (e.g., by exchanging leads and averaging measurements) voltage errors limit the practical accuracy of a DC resistance thermometer. AC techniques are free from voltage errors but may be subject to resistance time constant limitations [8].

6: Lead resistance errors. Industrial PRTs may be connected as 2-wire, 3-wire and 4-wire systems. The reference provides a discussion of these errors and their mitigation [9].

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FOOTNOTES

[1] John P. Tavener, Platinum Resistance Thermometers as interpolation standards for ITS-90, Isotech Jour Therm V1 N1 pp 31-37

[2] H. Preston-Thomas, The International Temperature Scale of 1990 (ITS-90), Metrologia 27, pp 3-10 (1990)

[3] C. H. Meyers, Coiled-Filament platinum resistance thermometers, Isotech Jour Therm V2 N1 pp 16-24

[4] Henry E. Sostmann, Standard platinum resistance thermometers, Isotech Jour Therm V2 N1 p 10 et seq.

[5] I am indebted for a conversation with Michael O'Shaughnessy, Sigmund Cohn Corporation, Mount Vernon, New York, for information about the preparation of pure platinum wire.

[6] Dr. Bert Brenner, for many years the revered metallurgist of the Sigmund Cohn Corporation (the world's premier supplier of thermometer wire) favored the pure platinum coefficient. He said to me once: "I have not spent my life learning how to purify platinum in order then to contaminate it!".

[7] From the catalog of TDI, Southport, England. For the addresses of TDI and its Western Hemisphere agent, please see Page 3 of this issue.

[8] See H. E. Sostmann, Fundamentals of Thermometry Part IV, Standard resistors, resistance bridges, thermometer measurements, Isotech Jour Therm V2 N2 pp 67-69

[9] Ibid., Pages 72-73