MSL Technical Guide 23

Using Industrial Platinum Resistance Thermometers for Laboratory Thermometry

Introduction

Over the last couple of decades, platinum resistance thermometers have largely replaced mercury-in-glass thermometers for most laboratory applications. Platinum resistance thermometers (PRTs) are more accurate, more stable, less fragile, less toxic, and less expensive to calibrate. There are few specific applications where mercury-in-glass thermometers remain cost effective or acceptable.

A good PRT thermometer is capable of accuracies of ±0.01 °C or better, but some care is required to achieve this level of accuracy. The purpose of this technical guide is to explain how to do this. The guide begins by briefly outlining the principles of platinum resistance thermometry, before looking at the various factors that must be addressed to make good temperature measurements.

Platinum Resistance Thermometers

Platinum resistance thermometers are very common industrial temperature sensors, and function by exploiting the change in the electrical resistance of platinum wire with temperature. PRTs are also known as resistance temperature detectors (RTDs) or Pt100s (platinum 100). Industrial PRTs are manufactured to cover temperature ranges from −200 °C to 850 °C, although they are rarely used in permanent installations above 450 °C because of increasing problems with the contamination of the platinum at high temperatures.

PRTs are made with a very wide range of designs suited to a wide variety of applications, but there are three basic types:

- Film PRTs are made from a very thin layer of platinum printed onto a substrate. They have a fast response and are cheap, but generally have only moderate long-term stability. Their resistance-temperature characteristic tends to depart from the standard tables due to strain-gauge effects with the platinum film being stretched or compressed with changes in temperature. They are least suited to high-temperature applications because of the large surface area of the film and the likelihood of contamination.
- Fully-supported or 'wound' PRTs are the most robust but tend to be the least accurate. The main cause of error is hysteresis due to the combination of strain-gauge effects and differential movement between the wire and the substrate caused by the different thermal expansion of the wire and substrate. This leads to unpredictable errors that may be as large as 0.05% of the temperature change. They are best suited to industrial applications, especially if mechanical shock or vibration is likely.
- Partially-supported or 'coil' designs achieve a good compromise between accuracy and robustness by partially supporting the wire along its length. This provides support for the wire while allowing for expansion and contraction at different temperatures. This makes sure that the hysteresis effects are very much reduced, but the PRT is still sensitive to vibration and mechanical shock.

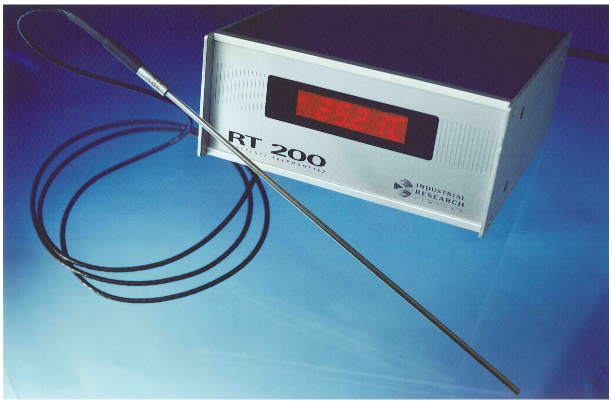

Figure 1. A typical direct-reading PRT thermometer.

Choosing a PRT

The partially supported PRTs are the best for laboratory thermometry, and if they are restricted to temperatures below about 250 °C, they are capable of accuracies of 0.01 °C or better. The PRTs should be bought fully sheathed, typically in stainless steel, and with a 4-wire connection. Ideally, the sheath should be a minimum of 300 mm in length and connected to the braid on the connecting cable so that the sheath can be grounded to provide electrical protection for the indicator and help reduce some types of electrical noise.

The cost of the probe varies markedly with quality, ranging from less than US$100 to more than US$1000. Lower quality sensing elements tend to have higher hysteresis, perhaps as much as 20 mK (0.02 °C), while the better sensors will have hysteresis as low as 1 mK. Lower cost probe assemblies also tend to use magnesia insulation in the sheath, which is prone to absorbing moisture and causes another type of hysteresis (see discussion below). Better quality probes will use alumina insulation, either as a powder or solid ceramic.

Choosing the Indicator

As with the probes, there is a wide variety of electronic indicators available for PRTs. The cost will range from about US$1000 for instruments with a nominal accuracy of 0.05 °C to perhaps $15,000 for instruments capable of accuracies approaching 1 mK. Do not exaggerate when you specify your needs – the cost is more or less directly related to the accuracy required. Further, the maintenance and calibration costs are higher for the more accurate instruments.

The instruments must use a 4-wire resistance measurement method to achieve accuracies of better than 0.1 °C.

Indicators basically come in two types: low-cost instruments using a dc sensing current to measure the resistance, and higher cost instruments using an ac sensing current. The ac systems eliminate thermoelectric effects, and are usually more accurate and faster. In recent years, the cost of the high-accuracy indicators has fallen with the development of integrated circuits that use a switched dc sensing current for measuring the resistance.

There is also a wide range of features available with the indicators. The instruments tend to range from low cost devices that read the temperature directly (in °C or °F) and are adjusted for use with just one probe. At the other end of the spectrum are instruments that measure and display the probe resistance, so can be used with many different probes. Some instruments have multiple channels, can be programmed to convert different probe readings to temperature, and have a variety of computer interfaces. If you intend to buy a ‘smart’ indicator with programmable features, it pays to download a copy of the instrument manual to check that the instrument is easy to program (also see software issues below).

What Goes Wrong?

For the most part, PRTs are very reliable and very accurate; however, there are a few things that affect their performance. The major effects that occur in use are described here.

Moisture

Any breakdown of the electrical insulation of the PRT assembly will cause the measured thermometer resistance to be low and, thus, the thermometer to indicate a low temperature. This commonly happens when moisture is trapped in the probe assembly. Moisture can be trapped at the time of manufacture or, more commonly, because the sheath-cable seal is imperfect and the probe is used in a moist environment. The moisture also migrates around inside the probe, depending on the temperature, causing a highly variable temperature error. This is the moisture-induced hysteresis mentioned above. The error can be as large as several degrees in extreme cases. Moisture is a particular problem for probes assembled with magnesia powder insulation. The magnesia absorbs and gradually accumulates moisture if the seal between the sheath and the cable is not perfect.

To check for moisture, disconnect the probe from the indicator and measure the resistance between any of the four sensor lead wires and the sheath. Use a 100 V insulation tester if you have one available. **Do not** use anything with a test voltage higher than 100 V. If the probe is dry, the resistance reading should be greater than 100 MΩ, and preferably greater than 1 GΩ.

The magnitude of the temperature error due to poor insulation can be estimated using the equation

$$\Delta T \approx -\frac{R(t)^2}{\alpha R_0 R_{\mathrm{ins}}},$$

where $R(t)$ is the resistance of the PRT at the given temperature, R_0 is the ice-point resistance of the PRT (typically 100 Ω), R_{ins} is the measured insulation resistance, and α is the temperature coefficient of the PRT (typically $\alpha = 3.85 \times 10^{-3}$ °C^{-1}. For example, an insulation resistance of greater than 1 MΩ is required to keep the temperature error for a 100 Ω sensor below 0.1 °C at 200 °C.

In most cases, the moisture can be removed by drying the entire probe in a drying oven at 60 °C (higher temperatures may damage the cable or connector). Usually a day or two of drying is sufficient to restore the insulation resistance to greater than 1 GΩ. If the insulation resistance does not improve then the moisture was probably sealed in at the time of manufacture.

In general, the seal region of the PRT assembly should not be exposed to moisture unless you are confident of the quality of the sheath-cable seal. Otherwise, ensure the sheath is long enough so that, in use, the seal is kept in dry air.

Mechanical Shock and Vibration

Despite the robust appearance of the PRT with its stainless steel sheath, it is a fragile device and should be treated as though it is made from glass. Each time a partially-supported PRT is bumped or knocked, the unsupported platinum wire in the sensor flexes, causing damage and a slight increase in the resistance of the PRT. This is the main cause of long-term drift in PRTs used for laboratory thermometry. In normal usage, the slow increase in resistance amounts to perhaps a 2 mK per year. In extreme cases, rough handling of the PRT will cause the resistance to increase by the equivalent of about 10 mK per month.

Tracking the increased probe resistance with time is relatively straight forward. All that is required is regular checks at 0 °C using an ice point (see MSL Technical Guide 1). With care, the PRT can be checked with an uncertainty of about 0.01 °C, but to do so you will need to follow the ice-point instructions closely. Depending on how much the PRT is used, ice-point checks should be carried out every 2 to 3 months. This helps to build confidence in the instrument by showing that the calibration certificate is still valid, and provides a warning of bad handling if the ice-point reading starts to drift rapidly. Maintaining a record of the ice-point readings also enables you to adjust the recalibration period to suit your needs. If the PRT drifts rapidly compared with your required accuracy, more frequent recalibration is required.

If necessary, the change in ice-point reading can be used to update a calibration certificate. The temperature error caused by the increase in resistance induced by shock tends to be a constant over the whole temperature range. For example, if the ice-point reading increases 0.02 °C, then the chances are that the PRT is in error by 0.02 °C over the whole of its temperature range.

Immersion Effects

The typical PRT sensing element is about 30 mm long, and many people expect a thermometer to read accurately with just 30 mm immersion. However, heat leaks up the stainless steel sheath of the PRT cause the reading to be in error. Depending on the temperature range, and the thermal conductivity of the object or fluid that the PRT is measuring, up to 200 mm of immersion may be required. This is why the probe should be at least 300 mm long.

If you have any concerns about the depth of immersion required to achieve a given accuracy you should carry out immersion tests on the thermometer. MSL Technical Guide 11 explains how to make these measurements, and Figure 2 gives examples of the results of such tests. The graph plots the percentage error in the temperature reading versus the length of thermometer immersed in an oil bath for PRT probes of two different diameters. One probe has a 4 mm diameter sheath, the other a 10 mm diameter sheath.

Results such as shown in Figure 2 provide a very useful guide. For example, to achieve an accuracy of 0.02 °C at 200 °C (an accuracy of about 0.01 %), the immersion of the 4 mm probe has to be about 16 cm.

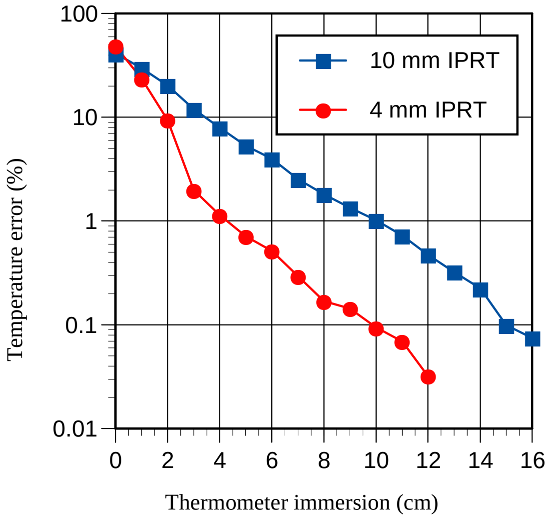

Figure 2. The immersion characteristics for PRT probes of two different diameters in a stirred oil bath.

Software Issues

Ideally, the software features on instruments should make them easy to use. Unfortunately, most commercial instruments have a few idiosyncrasies that can lead the user to make large errors in their measurements:

- Software constants should be auditable. A number of instruments allow the user to program calibration constants into the instrument but provide no means for the user to check that the values are correct.
- Software constants should be protected. Most modern instruments do not allow the calibration constants to be changed without a password or a physical key. However, there are also instruments where the constants can be erased with a single button push and the user cannot tell that this has happened. In other cases, the constants are accessible to all users.
- Out-of-range conditions should be clear. Software constants usually apply to a specific temperature range. If the instrument goes outside this range, either (i) the software extrapolates and the measurement uncertainty increases rapidly, or (ii) the instrument gives the user an out-of-range message, or (iii) the software reverts to its default values and large errors are introduced. This latter situation is unfortunately common, and the errors can be as much as a degree or more. In cases (ii) and (iii) the user may be completely unaware of the potential for large errors.
- Keep a hard copy of calibration constants. Ideally, your calibration laboratory should, as part of the calibration conditions, record the calibration constants programmed into the instrument on the calibration certificate. If not, the user should keep this record as a means to audit the constants.
- Keep a unique copy of the manual for each instrument. Instrument manufacturers are constantly updating their instruments, and the improvements may include software updates. This means that the instructions for operating and programming an instrument may not apply to the same model of instrument bought a year later.
- Some instruments may have several 'layers' of software constants. The temperature measurement may involve first a resistance measurement, corrections to resistance measurement, conversion to temperature, and then, finally, corrections to the temperature measurement. Some or all of these layers may be accessible to the user. Changing the software constants for a 'deep layer' will necessitate changes to all subsequent layers.

Calibration

Finally, it is important to get the thermometer calibrated. The standard manufacturing tolerance on industrial PRTs is 0.3 °C plus 0.2 % of the reading in degrees (°C or °F). So at 100 °C, the error for a PRT within the manufacturer's specification may be as large as 0.5 °C. Better tolerances are available but are still well short of the potential accuracy of a well-calibrated instrument.

References

[1] MSL Technical Guide 1: "The Ice Point", http://msl.irl.cri.nz.

[2] MSL Technical Guide 11: "Thermometer immersion and dry-block calibrators", http://msl.irl.cri.nz.

[3] MSL Technical Guide 18: "Resistance measurement for thermometry", http://msl.irl.cri.nz.

[4] J V Nicholas and D R White, *Traceable Temperatures* 2nd Ed., John Wiley & Sons, Chichester, 2001.

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