Technical Guide

Working Thermometers – Calibration Requirements

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1 Introduction

It is fundamental to good laboratory practice that the calibrations of both working and reference thermometers be traceable to the New Zealand national standards of temperature and thus to SI (International System of Units; Système international d'unités) units. For more information on measurement traceability, please see the IANZ technical policy (see references).

Laboratories achieve this by sending their reference thermometer(s) to an appropriate calibration agency. They then use the reference thermometer(s) to check their own working thermometers.

This IANZ Technical Guide describes a procedure that may be used for the comparison of working grade thermometers with calibrated reference thermometers. In addition, procedures for ice-point checks on reference thermometers and single-point checks on working thermometers are also described.

2 Selection of a reference thermometer

The selection of an appropriate reference thermometer will be influenced by the range of temperature measurements that are to be made and the uncertainty of measurement required.

BS 593:1989 has information regarding thermometer compliance requirements.

BS 1900:1976 (see references) provides similar information about secondary reference thermometers whilst ASTM E1 (see references) provides details of ASTM and IP thermometers. If an uncertainty of calibration of less than 0.02 °C is required, then a BS 1900 thermometer must be used.

The following is an example:

A laboratory intends to purchase a reference thermometer with which to calibrate a group of its own working thermometers. The reference thermometers must first be submitted to an appropriate calibration agency to be calibrated.

The working thermometers in question will be used to measure the temperature of a water bath set at 44.5 °C. They must be calibrated with an uncertainty of 0.2 °C.

In general, the uncertainty of calibration of the reference thermometer should be a factor of five smaller than the uncertainty of calibration that is required for the working thermometer. In this case, as an uncertainty of calibration of 0.2 °C is required for the working thermometer, the uncertainty of the reference thermometer's calibration must be ± 0.04 °C (0.2x1/5).

A good quality reference thermometer can generally be calibrated with an uncertainty of one fifth of a scale division so if an uncertainty of ± 0.04 °C is required this implies that the reference thermometer must have scale divisions of 0.2 °C (0.04x5).

For the application under consideration, therefore, a reference thermometer covering the region of 44.5 °C with graduations of at least 0.2 °C is required. The BS 593 thermometer A70C/TOTAL listed above meets this specification.

In summary, a reference thermometer must have scale divisions equal to, or less than, the uncertainty of measurement required in the calibration of the working thermometer with which it is to be compared.

3 Thermometer Calibration Schedule

For guidance on the frequency of calibration of thermometers (including external calibration of reference thermometers), please see the IANZ Specific Criteria document applicable to your type of laboratory (see references).

In-house calibration of infra-red working thermometers is not recommended unless the laboratory has access to an appropriate a black body reference system. For more information please see Section 4.

4 Considerations for different thermometer types

4.1 Liquid in Glass (LiG)

A liquid in glass thermometer comprises a bulb, a fine capillary and one or more expansion chambers at the top of the column. There may also be an expansion chamber between the ice point and the beginning of the scale. To give the required sensitivity, the bulb of a reference thermometer is extremely thin (less than 0.5 mm) so careful handling is imperative.

When a thermometer is first made, the glass is in a highly stressed state. This stress slowly relaxes in time causing the bulb to contract. This pushes the mercury higher up the capillary and causes the ice point to rise. There is a consequent change to all other scale points. Such "ageing" of the bulb is fairly rapid immediately after manufacture but gradually slows down with time. An ice-point check every six months, which is required by most thermometer calibration schedules, is a good monitor of the bulb contraction. In general, any rise detected can be subtracted linearly along the entire scale of the thermometer.

Heating a thermometer to its maximum temperature and then reducing it to ambient temperature causes a temporary depression of the ice point through bulb expansion. This may take several days to relax.

A total immersion thermometer is one that is designed to be immersed in the medium being monitored to the level of the current reading. A partial immersion thermometer is designed to be immersed to the depth of a specific mark on the stem (usually at 76 mm or 100 mm).

4.2 Thermocouples

The following information has been extracted from the IANZ Specific Criteria 5 for Metrology and Calibration Laboratories, edition 4, and relates to the uncertainty due to thermocouple inhomogeneity.

All base-metal thermocouples (Type T, N, K, J, E) suffer from errors due to metallurgical changes that occur at temperatures above 150 °C. Because the thermocouple emf is produced by those parts of the thermocouple located in temperature gradients (not at the thermocouple tip as commonly thought), thermocouples exposed to these temperatures may be sensitive to immersion conditions and history of thermal exposure. For the highest accuracy at these temperatures, thermocouples should be used only for a single application and fixed in position so the immersion conditions cannot change. Where accuracy better than the indication given by the manufacturers 'limits of error' is required, they must be (i) calibrated in situ, or (ii) taken new from a batch for which a sample has been calibrated, and (iii) replaced regularly according to observed drift rates and users accuracy requirements.

The effects of inhomogeneity caused by cold work or previous heat treatment, compensating leads, cold junction compensation and thermal losses on temperature measurements should be included in the uncertainty assessment. Calibrations of thermocouples must include the compensating lead to be used.

An approximate expression for the standard uncertainty due to inhomogeneity in base-metal thermocouples can be obtained using the following formula:

$$u = 0.15 + 0.0003 \cdot t + 0.000004 \cdot t^2$$

where:

u = standard uncertainty for thermocouple inhomogeneity

t = temperature in degrees Celsius.

4.3 Platinum Resistance Thermometers (PRTs) – also known as RTDs

PRTs usually appear to be physically robust due to a sturdy stainless steel sheath; however the platinum temperature sensor inside the sheath can be very delicate, depending on what type it is. PRTs should always be handled with care: not dragged, dropped, banged, clamped, bent or swung. The joint of the cable to the top of the sheath is also delicate and if wires inside are damaged the readout may be affected.

PRTs can also suffer from moisture ingress if used in a damp or wet environment, and can have significant errors if not immersed sufficiently.

Please refer to the MSL Technical Guide 23: Using Industrial Platinum Resistance Thermometers for Laboratory Thermometry for more information (see References).

4.4 Infra-red (IR) thermometers

Infra-red thermometers can appear easy to use ("point and shoot") but can suffer a lot of errors if not used properly. Amongst these errors are reflection, size of source and focus effect errors. MSL Technical Guides explain further some of these errors (see references, and other technical guides for more information).

5 Inspection and Repair of Thermometers

5.1 Liquid in Glass (LiG) thermometers

The first step in the calibration procedure is to visually check the thermometer for gross defects. Points to look for are non-uniform or missing graduations, missing numbers and improper etching. Next, the thermometric liquid should be checked for defects such as inclusions, a broken column or separated liquid in the expansion or contraction chamber. More stringent and extensive specifications are given in appropriate standards such as BS 593:1989 Specifications for Laboratory Thermometers and BS 1900:1976 Specification for Secondary Reference Thermometers.

Gas inclusions and broken columns are best removed by carefully cooling the bulb of the thermometer in a thermos flask of either ice and methanol, dry ice and methanol or liquid nitrogen, depending on the temperature range of the thermometer. This will draw all the liquid into the bulb and enable the gas inclusion to be expelled or the broken thread re-joined. Avoid rapid cooling which may freeze the liquid in the thermometer and break the bulb. If the broken thread sticks, tap the thermometer gently. Separation of the column of a reference thermometer can occur in transit and requires the same treatment for repair. Spirit left in the expansion chamber or near the top of the thermometer can be gently heated to distil it off.

5.2 Other types of thermometers

Other types of thermometers should be checked visually to ensure no obvious damage has occurred.

6 Ice Point Checks (LiG and PRTs only)

Checks on both a reference and working thermometer should be made every six months on the ice point (0 °C mark) of the thermometer. The ice point check need not, however, be made on a working thermometer used continually at one temperature. Such a thermometer would be more appropriately checked at this temperature every six months against a single reference thermometer (which itself would still require the ice point check).

Refer to MSL Technical Guide 1 (see references) for information on the ice point and how to make an ice point.

Any change in the temperature correction at the ice point, which has occurred between the current calibration and the initial calibration of the thermometer made by the external calibration agency, should be applied at all other calibrated points.

Changes that are considered insignificant depending on method being used or accuracy required do not need to be applied. The need to apply corrections and the tolerance for changes in the ice point are the laboratory's responsibility to determine.

For example, a laboratory may perform an ice point check on a reference thermometer which was subjected to a complete calibration at the time it was purchased.

The initial calibration report may have indicated the following results:

Thermometer Reading (°C)	Correction (°C)
-0.04	+0.04
5.00	+0.04
10.00	+0.06
15.00	+0.02
20.00	+0.06
25.00	+0.08
30.00	+0.06
35.00	+0.04
40.00	+0.04

To obtain the correct temperature the correction must be applied to the thermometer reading.

The laboratory might obtain three ice point readings as follows:

-0.02 °C; -0.02 °C; -0.02 °C

The new ice point reading is the average of the above, i.e. –0.02 °C. The thermometer is, therefore, reading low by 0.02 °C and so the correction to be applied is +0.02 °C. This compares with the earlier calibration which gave a correction at 0 °C of +0.04 °C. Corrections at all other temperature reported by the calibration agency must now be altered by (0.02 – 0.04) i.e. –0.02 °C, thus:

Thermometer Reading (°C)	Correction (°C)
-0.02	+0.02
5.00	+0.02
10.00	+0.04
15.00	+0.00
20.00	+0.04
25.00	+0.06
30.00	+0.04
35.00	+0.02
40.00	+0.02

Ice points made with reasonable care should reproduce 0 °C ± 0.05 °C or better.

7 Uncertainty of Measurement

All testing and calibration laboratories meeting the requirements of ISO/IEC 17025 to determine the uncertainty of each of their measurements. Obviously for equipment being used to make measurements in testing, the starting point for this determination will be the uncertainty contribution from each reference instrument.

Accredited calibration laboratories are required to report the uncertainty for their calibrations and all IANZ endorsed calibration certificates will provide this information. As appropriate, this data can be directly used in the testing laboratory's own determination of uncertainty of measurement in testing.

When a testing laboratory chooses to carry out its own in-house calibration, the uncertainty of that calibration will need to be determined using appropriate methods. Depending on the degree of rigour required, there are a number of different approaches to this.

8 Measurement Traceability

Please see IANZ Technical Policy No. 1 *Traceability of Measurement* (AS TP 1) for more information on metrological traceability.

9 Comparison of Working Thermometers with Reference Thermometers

9.1 General Procedure

Please see the section Inspection and Repair of Thermometers above as the first step in the calibration procedure.

The working thermometer and the reference thermometer with which it is to be compared are held side-by-side in a temperature controlled enclosure (for example, water, oil or air). The bath is allowed to stabilise at the required calibration temperature before the readings of the thermometers are compared.

If the working thermometer is being checked at one point only for its regular six-monthly check then only one set of readings is required. If the thermometer is being subjected to an initial check before being put into use then readings should be taken across the required range or at points of use.

If a liquid in glass thermometer is to be compared at a particular temperature (for example 37 °C), then two sets of readings are taken either side of the required temperature (36.5 °C and 37.5 °C). These two sets of readings are averaged to find the correction to the working thermometer's reading at the particular temperature. Note: other types of thermometers do not need the temperature either side of the nominal temperature calibrated.

The procedures outlined below presume that up to four working thermometers are being checked at one time. They are equally valid, however, for checks on fewer than four. The calibration of more than four thermometers at one time is not recommended.

9.2 Uncertainty of Calibration Greater than ± 0.5 °C

9.2.1 Equipment

(a) A well-stirred, temperature-controlled enclosure which is stable to at least half the required uncertainty in the calibration of the working thermometer. Spatial temperature gradients (both vertical and horizontal) within the area of the bath being used for comparison should be checked before calibration begins. These must be less than one quarter of the uncertainty of calibration required. A very slowly rising temperature is desirable but in no case should the temperature be falling during calibration as this can cause hysteresis effects.

(b) At least one reference thermometer, the uncertainty of calibration of which is, at most, one-fifth of the uncertainty of calibration required for the thermometer under test. The reference thermometer(s) must be calibrated by an accredited calibration laboratory Liquid-in-glass reference thermometers should be of the partial immersion type if the working thermometers are partial immersion and/or if the depth of immersion in the comparison bath is limited.

(c) If using liquid-in-glass thermometers, a magnifying eyepiece to reduce parallax errors and improve readability.

(d) A flat plate, drilled to take both reference and working thermometers, which can be clamped over the bath. O-rings or rubber grommets can be used to hold the thermometers at the correct height in the plate.

9.2.2 Procedure

Note: In general, no attempt should be made to calibrate a working thermometer (in-house) to an uncertainty of less than half a scale division.

The following is an example:

A working thermometer needs to be compared with a reference thermometer at 37 °C. Insert the reference thermometer into the supporting plate with no more than four working thermometers in the order Reference, Test 1, Test 2, Test 3, Test 4. Stabilise the bath temperature to just below 37 °C.

For liquid-in-glass thermometers immerse to the reading if they are of the total immersion type or to the appropriate mark (e.g. 76 mm) if partial immersion. Thermometers should be immersed appropriately (vertical for liquid-in-glass, sufficient immersion for others) and the bath level should be increased if immersion is insufficient.

If total immersion thermometers are used at partial immersion, their readings will require correction (see 8.4).

When the bath temperature is stable, read the thermometers in the following order (liquid-in-glass thermometers should be gently tapped before reading):

Ref 1 2 3 4 4 3 2 1 Ref

and record the thermometer readings as they are made.

Repeat the measurements at a temperature above 37 °C (say 37.5 °C). Similar checks should be made at least every 10 °C of the scale if the thermometer is to be used over a range of temperatures (for example if the thermometer is used for multiple purposes, not just at a few key temperatures).

9.2.3 Calculation of Corrections

Average the two sets of readings for each of the five thermometers as shown below. Correct the reference thermometer reading using the correction from its calibration certificate, allowing for any change in the ice point as shown previously. It may be necessary to interpolate the correction to the reference thermometer reading for the actual bath temperature chosen; for example, if the correction to the reference thermometer at 35 °C is + 0.01 °C and at 40 °C the correction is + 0.03 °C, then at 37 °C the correction will be + 0.02 °C.

Subtract the corrected reference thermometer average reading from the average readings of the working thermometers to obtain the error in each thermometer. The correction is found by changing the sign of each error, as shown in Tables 1 and 2.

Table 1: Calibration at 36.5 °C

	Reference	T1	T2	T3	T4
Reading 1 (°C) Reading 2 (°C)	36.65 36.70	36.5 36.6	36.7 36.7	36.6 36.6	37.0 37.0
Average	36.68	36.55	36.7	36.6	37.0
Correction to reference from calibration certificate +0.02 °C. Therefore the average temperature in bath at calibration will be (+0.02) 36.70 °C.					
Subtract average bath temperature from average test thermometer reading to obtain error in test thermometers		(-36.70) -0.15	(-36.70) 0.00	(-36.70) -0.10	(-36.70) +0.30
Correction (1) to test thermometers (change sign)		+0.15	0.00	+0.10	-0.30

Repeat this procedure for the results of the second test carried out at 37.5 °C.

Table 2: Calibration at 37.5 °C

	Reference	T1	T2	T3	T4
Reading 1 (°C) Reading 2 (°C)	37.45 37.48	37.3 37.3	37.4 37.4	37.3 37.3	37.5 37.5
Average	37.46	37.3	37.4	37.3	37.5
Correction to reference from calibration certificate +0.02 °C. Therefore the average temperature in bath at calibration will be (+0.02) 37.48 °C.					
Error in test thermometers		(-37.48) -0.18	(-37.48) -0.08	(-37.48) -0.18	(-37.48) +0.02
Correction (2) to test thermometers		+0.18	+0.08	+0.18	-0.02
Correction (1) to test thermometers from above		+0.15	0.00	+0.10	-0.30
Average of corrections (1) and (2) to test thermometers at 37 °C, rounded to nearest 0.1 °C (readability of thermometer)		(+0.16) +0.2	(+0.04) 0.0	(+0.14) +0.1	(-0.16) -0.2

The procedure outlined above should be carried out at each point on the working thermometer's scale that is to be calibrated.

The corrections to a thermometer being used over a wide range of temperatures can be plotted against temperature to produce a calibration curve. This procedure facilitates interpolation of corrections at intermediate temperatures.

9.3 Uncertainty of Calibration between ± 0.5 °C and ± 0.1 °C

9.3.1 Equipment

(a) A well-stirred, temperature-controlled enclosure which is stable to at least half the required uncertainty in the calibration of the working thermometer. Spatial temperature gradients (both vertical and horizontal) within the area of the bath being used for comparison should be checked before calibration begins. These must be less than one quarter of the uncertainty of calibration required. A very slowly rising temperature is desirable but in no case should the temperature be falling during calibration as this can cause hysteresis effects.

(b) Two reference thermometers, the uncertainty of calibration of which is, at most, one-quarter of the uncertainty of calibration required for the thermometer under test. The reference thermometer(s) must be calibrated by an accredited calibration laboratory. Liquid-in-glass reference thermometers should be of the partial immersion type if the working thermometers are partial immersion and/or if the depth of immersion in the comparison bath is limited.

(c) If using liquid-in-glass thermometers, a magnifying eyepiece to reduce parallax errors and improve readability.

(d) A flat plate, drilled to take both reference and working thermometers, which can be clamped over the bath. O-rings or rubber grommets can be used to hold the thermometers in the plate at the correct height.

9.3.2 Procedure

The following is an example:

A working thermometer needs to be compared with a reference thermometer at 37 °C. Insert the reference thermometers into the supporting plate with no more than four working thermometers in the order: Reference 1, Test 1, Test 2, Test 3, Test 4, Reference 2. Stabilise the bath temperature to just below 37 °C.

For liquid-in-glass thermometers immerse to the reading if they are of the total immersion type or to the appropriate mark (e.g. 76 mm) if partial immersion. Thermometers should be immersed appropriately (vertical for liquid-in-glass, sufficient immersion for others) and the bath level should be increased if immersion is insufficient.

If total immersion thermometers are used at partial immersion, their readings will require correction (see 8.4).

When the bath temperature is stable, read the thermometers in the following order (liquid-in-glass thermometers should be gently tapped before reading):

Ref 1, Test 1, 2, 3, 4, Ref 2, Ref 2, Test 4, 3, 2, 1, Ref 1

Repeat the measurements at approximately 37.1 °C. Similar checks should be made at least every 10 °C of the scale if the thermometer is to be used over a range of temperatures (for example if the thermometer is used for multiple purposes, not just at a few key temperatures).

9.3.3 Calculation of Corrections

Average the two sets of readings for each of the six thermometers as shown below. Correct the reference thermometer readings using data from their calibration certificates. Consider that at 37 °C the corrections required are +0.02 °C for Reference 1 and +0.05 °C for Reference 2. (These figures will probably have been interpolated from corrections given by the reference thermometers' calibration certificates at 35 °C and 40 °C.)

The average of the two corrected reference thermometers' readings is now subtracted algebraically from the average for each test thermometer to give the error as shown in Tables 3 and 4.

Table 3: Calibration at 36.9 °C

	Ref 1	T1	T2	T3	T4	Ref 2
Reading 1 (°C) Reading 2 (°C)	36.88 36.92	36.8 37.0	36.8 36.9	36.7 36.8	37.0 37.0	36.85 36.87
Averages	36.90	36.9	36.85	36.75	37.0	36.86
Reference correction from calibration certificate =	+0.02					+0.05
Reference Temperature (1)	36.92			Reference Temperature (2)		36.91
Average of references (Temperature in bath)	36.92					
Subtract average bath temperature from average test thermometer reading to obtain error in test thermometers		(-36.92) -0.02	(-36.92) -0.07	(-36.92) -0.17	(-36.92) +0.08	
Correction (1) to test thermometers (change sign)		+0.02	+0.07	+0.17	-0.08	

For the second test at 37.1 °C the calculations might be as follows:

Table 4: Calibration at 37.1 °C

	Ref 1	T1	T2	T3	T4	Ref 2
Reading 1 (°C) Reading 2 (°C)	37.08 37.16	37.1 37.2	37.1 37.1	37.3 37.3	37.2 37.2	37.05 37.05
Averages	37.12	37.15	37.1	37.3	37.2	37.05
Reference correction from calibration certificate =	+0.02					+0.05
Reference Temperature (1)	37.14			Reference Temperature (2)		37.10
Average of references (Temperature in bath)	37.12					
Subtract average bath temperature from average test thermometer reading to obtain error in test thermometers		(-37.12) +0.03	(-37.12) -0.02	(-37.12) +0.18	(-37.12) +0.08	
Correction (2) to test thermometers (change sign)		-0.03	+0.02	-0.18	-0.08	
Correction (1) from Table 3 above		+0.02	+0.07	+0.17	-0.08	
Average of corrections (1) and (2) to test thermometers at 37.0 °C		0.00	+0.04	0.00	-0.08	
Round to 0.1 °C (readability of thermometer)		0.0	0.0	0.0	-0.1	

The corrections to a thermometer being used over a wide range of temperatures can be plotted against temperature to produce a calibration curve. This facilitates interpolation of corrections at intermediate temperatures.

9.4 Correction of Total Immersion Thermometers used at Partial Immersion

If it is not possible to fill the comparison bath sufficiently to immerse a total immersion reference thermometer to the reading, a correction can be made, using the formula below (from Reference 7).

$t = t_2 + N(t_2 - t_1)k$

Where:

t is the indicated temperature

t_1 is the mean temperature of the emergent column in use

t_2 is the mean temperature of the emergent column when calibrated i.e. the thermometer reading for a total immersion calibration certificate

N is the length of the emergent column expressed in degrees, as determined by the thermometer's scale

k is the coefficient of expansion of the thermometric liquid used, in the glass of which the thermometer stem is made.

To obtain t_1 another small thermometer should be attached to the stem of the thermometer about one-third of the way up the exposed column. This will read (approximately) the average temperature of the emergent length of mercury (or spirit).

k = 0.00016 for mercury

k = approximately 0.001 for spirit.

10 References

The following guides and published by the Measurement Standards Laboratory of New Zealand as MSL Technical Guides (https://measurement.govt.nz/resources/#collapse-control-1-4):

Infrared thermometers

Technical Guide 2: Infrared Thermometry Ice Point

Technical Guide 15: Correcting Radiation Thermometers for Reflection Errors

Technical Guide 22: Calibration of Low-Temperature Infrared Thermometers

Technical Guide 26: Size-of-Source Effect in Infrared Thermometers

Technical Guide 35: Emissivity of Blackbody Cavities

Contact thermometers

Technical Guide 1: The Ice Point

Technical Guide 11: Thermometer Immersion and Dry-Block Calibrators

Technical Guide 14: Making Sense of Thermocouples

Technical Guide 23: Using Industrial Platinum Resistance Thermometers for Laboratory Thermometry