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Rail temperature study

Rail Temperature Study

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Executive Summary

AEA Technology Rail have undertaken a laboratory study of rail temperature behaviour and measurement on behalf of the Rail Safety and Standards Board (RSSB). This study aimed to increase the accuracy of rail temperature measurement by:

1. Investigating the relationship between rail surface temperature profile and bulk rail temperature;
2. Evaluating the accuracy and usability of a range of different thermometers either designed for rail use or potentially suitable for rail use.

The tests on rail temperature behaviour involved heating a length of test rail with radiant heaters and recording surface and internal temperatures. The thermometer evaluation tested eight different thermometers, representing samples of thermometers either designed for rail use or potentially suitable for rail use.

In terms of accuracy of different thermometers for measuring rail web temperature, the traditional magnetic dial thermometer produced the best overall accuracy of ±1°C, but this finding is limited to the range 0 to 40°C (approximately) for the particular thermometer tested. The test results also suggested that an infrared thermometer (overall test accuracy of +1°C up to ~30°C and +2°C above ~30°C) has potential for accurate rail temperature measurement for stressing purposes. The significant caveat is the variability of the surface conditions affecting readings by up to 7°C during testing - an automatically adjusting emissivity would be expected to counter this sensitivity. Instruments with this feature, available off-the-shelf, have been identified following testing. The K-type thermocouples tested have a practical accuracy of ±1°C over the test temperature range (-5 to +55°C) but did not consistently achieve this when fitted to uninsulated metal sensors which were subject to heat loss to the air and/or poor surface contact with the rail.

In terms of usability of different thermometers, the best method of attachment to the web was a sufficiently strong magnet, for example, the magnetic dial thermometer and a U-shaped magnetic block K-type thermocouple sensor (used with an industrial digital thermometer display). The industrial digital thermometer with protective rubber case is regarded as the most robust instrument of those tested. An infrared thermometer in a tough plastic pistol grip case was second only in robustness to the industrial digital thermometer. Thermometers with hard and/or brittle cases, such as the magnetic dial or mercury in glass thermometer, need care when handling and may be more easily damaged if accidentally dropped.

Ease of operation is essential for a rail thermometer - it should be possible to simply attach the instrument (or its sensor) and repeatedly take readings. The magnetic dial thermometer and the industrial digital thermometer (used with clamp or magnet thermocouples) are among the better performing instruments overall which achieved this.

Other makes and models, of varying and often better specification, of each type of thermometer tested are available from suppliers. In sourcing those thermometers marketed specifically for rail use, it was noted that these tend to be at the lower cost, lower specification end of the market. This is likely to affect the overall performance of these instruments.

Analysis of the rail temperature behaviour test results suggests that the bulk temperature at a given rail cross-section may usefully be estimated by measuring the temperature on the shaded side of the web, then applying the following correlation:

$$\text{Bulk temperature} = \text{Web (shaded side) temperature} + 2.1^{\circ}\text{C}$$

This correlation suggests that the existing method in the Network Rail standard RT/CE/S/011, whereby temperature is measured on the shady side of the web or foot, may be underestimating the bulk temperature by at least 2°C, possibly leading to stressing of continuous welded rail to a higher stress free temperature (SFT) than the intended target of 27°C. However, it is believed that the target is itself based on rail temperature measurements taken on the shady side of the web. This utilisation of web surface temperature as representing bulk rail temperature would have to be taken into account if implementing the above correlation. Further evaluation of the above bulk temperature correlation would also be desirable if seeking to implement the correlation. Four of the five current tests obtained a reference bulk temperature from a correlation with internal rail temperatures (albeit with a high quality fit to the data) rather than from direct measurement of expansion of the bending rail when heated on one side.

Recommendations:

1. The current Network Rail standard RT/CE/S/011 permits temperature measurement on the shady side of the rail web or foot. The current study recommends that temperature is only measured on the shady side of the web, not the foot.
2. It is recommended that temperature readings taken on the shady side of the web continue to be regarded as estimates of the cross-section bulk rail temperature until or unless further research strengthens the case for applying a correction to these readings to better estimate bulk temperature as it relates to target SFT values.
3. Thermometers with a practical accuracy of at least ± 1°C should be used for rail temperature measurement.
4. Thermometers used for rail temperature measurement should achieve a secure, close, flush contact of the actual temperature sensor surface with the rail surface.
5. Temperature sensors used in rail temperature measurement should be immune from external temperature effects, as far as is practically possible.
6. Thermometers should be maintained within calibration according to manufacturers' guidelines where provided, not necessarily limited to the annual check against a master thermometer as required in RT/CE/S/011.
7. Thermometers used for rail temperature measurement should be sufficiently robust to withstand use in the rail environment without their performance degrading as a consequence between checks and/or calibrations.
8. The use of thermometers with better specifications than those currently marketed for rail use should be considered.
9. Further tests should evaluate infrared thermometers with automatically adjusting emissivity, higher specification magnetic dial thermometers and magnetic K-type thermocouples designed to overcome the disadvantages of those tested in the current study.

Acknowledgements

The author wishes to acknowledge the key contributions of Pete Booley, David Howell and Julian Tullet of AEA Technology Rail in setting up and running the laboratory tests, in AEA Technology Rail's Test Hall, which form the core of this study.

Glossary

CWR Continuous Welded Rail

LVDT Linear Variable Displacement Transducer

PRT Platinum Resistance Thermometer

RSSB Rail Safety and Standards Board

SFT Stress Free Temperature

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1 Introduction

AEA Technology Rail have undertaken a laboratory study of rail temperature behaviour and measurement on behalf of the Rail Safety and Standards Board (RSSB). This study aimed to increase the accuracy of rail temperature measurement by:

1. Investigating the relationship between rail surface temperature profile and bulk rail temperature;
2. Evaluating the accuracy and usability of a range of different thermometers either designed for rail use or potentially suitable for rail use.

2 Method

2.1 Rail Temperature Behaviour

The tests on rail temperature behaviour involved heating a length of test rail with radiant heaters and recording surface and internal temperatures. The target rail temperature test range was minus 5°C at the lower end, to be achieved by cooling the rail in an environmental chamber prior to testing, and 55°C at the upper end, this being regarded as the highest rail temperature of interest.

The test length of rail was CEN60E1 section and was 898 ± 1 mm long. This length approximated the width of two of the radiant heaters in order to achieve uniform heating along the rail. The head of the rail was polished along its length in order to replicate rail which has been under traffic. The rail was supported on rail pads on wooden blocks set in a bed of small size ballast to allow airflow underneath it as may be expected on track.

K-type thermocouples were used to measure the rail temperatures. A thermocouple consists of a junction of two dissimilar metal alloys (Ni/Cr (+ve) and Ni/Al (-ve) for K-type). When located in contact with the material whose temperature is required to be measured, the junction produces a small voltage which increases with increasing temperature. No direct electrical input is required to produce this voltage. Two extension wires transmit the voltage to an appropriate display device. Thermocouples are widely used in industry and are relatively low cost.

Six K-type thermocouple temperature sensors were attached to the surface of the rail at the centre cross-section. Three K-type thermocouples were inserted into the rail on the centre cross-section, one in each of the head, web and foot. The web sensor was on the neutral axis and the head and foot sensors were inserted to 15 mm depth from their respective surfaces. Two further thermocouples were inserted into the head, each 50 mm from the ends of the rail in order to monitor any longitudinal temperature variations. The total number of temperature sensors in or on the rail was therefore 11, with nine of these at the centre cross-section. A platinum resistance thermometer (PRT) was used during testing to measure ambient laboratory temperature. The measurement accuracy of the K-type thermocouples is ± 1°C and all were calibrated in-house against the PRT which has ± 0.1°C accuracy. Figure 1 shows the sensor locations on the rail and Table 1 lists these locations.

A linear variable displacement transducer (LVDT; accuracy of ± 10 μm) was placed at each end of the rail to measure longitudinal expansion of the test rail as it was heated. The following example calculation of rail extension (based on the Network Rail standard RT/CE/S/011 Continuous Welded Rail (CWR) Track, Section 9.11) for a 60°C temperature rise provided an estimate of the expected expansion:

$$\text{expansion} = 0.898 \text{ m} \times 11.5 \times 10^{-6}\ {}^{\circ}\text{C}^{-1} \times 60\ {}^{\circ}\text{C} = 0.62 \times 10^{-3} \text{ m}$$

The accuracy of the LVDT's was 1.6% of the expected expansion and was therefore regarded as sufficient to measure expansion of the test length. The LVDT's exerted a negligible force on the rail ends, therefore the rail was free to expand. If the rail were constrained longitudinally, as it would be in stressed, continuously welded track, then the longitudinal stress would have to be accounted for if seeking to relate expansion to temperature.

The bulk temperature change was calculated (in Test 1) from the expansion of the rail. The bulk temperature is the integral of the temperature throughout the test rail. If a given length of rail has a perfectly uniform temperature, this uniform temperature is the bulk temperature corresponding to that length. If the rail is heated (or cooled) such that it contains temperature gradients, addition of its change in length to (or subtraction from) its original length, together with knowledge of its thermal expansion coefficient, permits calculation of its new bulk temperature. The bulk temperature may be regarded as the average temperature throughout the rail but it cannot necessarily be calculated accurately by simply averaging a selection of temperature measurements taken on and/or in the rail.

Figure 1 CEN60E1 section with labels showing temperature sensor locations. Locations with no surround are on visible side of rail. Locations with dashed grey surround are inside rail. Locations with dashed white surround are on hidden side of rail.

Sensor Label	Head/Web/Foot	Surface/Internal
T1	Head	Internal
T2	Head	Surface
T3	Head	Surface
T4	Web	Surface
T5	Web	Surface
T6	Foot	Surface
T7	Foot	Surface
T8	Foot	Internal
T9	Head	Internal
T10	Head	Internal
T11	Web	Internal

Table 1 List of temperature sensor locations on or in the test rail.

Five tests were conducted using different rail and heating configurations as follows:

Test 1: Heat both sides of rail, placing heaters alongside and obtain steady state heat flows.
Test 2: Heat one side of rail, heaters alongside angled down at 45° and obtain steady states.
Test 3: Cool rail in ambient laboratory temperature after heating one side with angled heaters.
Test 4: Heat one side with angled heaters with wind chill on other side.
Test 5: Heat both sides with angled heaters placed at end of rail.

Test 1 Heat both sides of rail, placing heaters alongside and obtain steady state heat flows.

Figure 2 Test 1 rail and heater configuration.

The first test involved heating the rail from both sides. Figure 2 shows the rail and heater configuration. While heating, readings from all probes were logged simultaneously on a data logger which sampled for three seconds in every ten seconds. The rail was allowed to warm from sub-zero temperatures until the rate of temperature increase slowed significantly, then the heaters were switched on. Given the ambient temperature of about 15°C, steady state heat flow scenarios were obtained at 5°C intervals from 20°C upwards. The neutral axis probe readings were used to mark these intervals. The heating was moderated to attain as uniform a steady state set of readings as possible for several minutes for each scenario.

Test 2 Heat one side of rail, heaters alongside angled down at 45° and obtain steady states.

Test 1 was repeated but the rail was heated on one side only. Figure 3 shows the rail and heater configuration. The heat source was aimed at the side of the rail from a position of 45° from the horizontal.

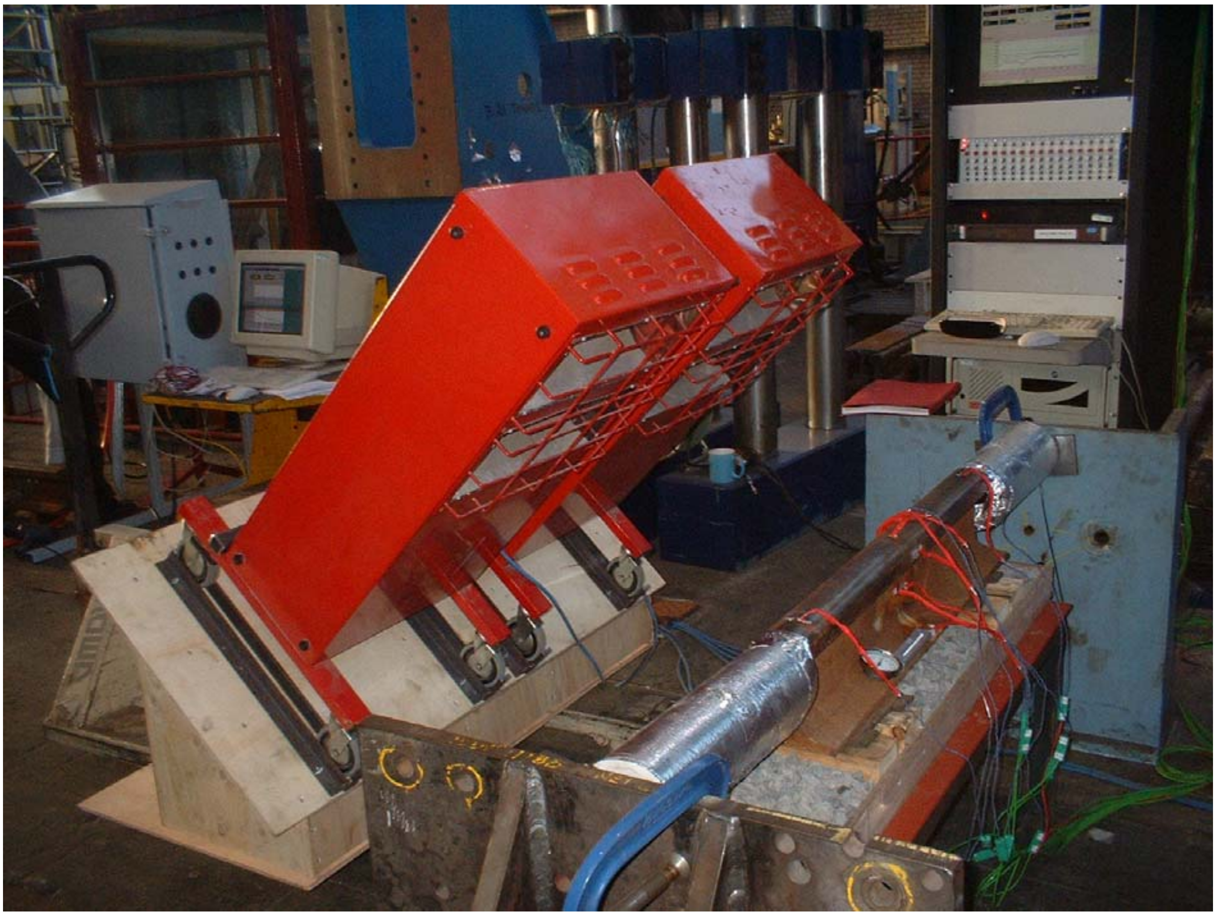


Figure 3 Tests 2, 3 and 4 rail and heater configuration.

<u>Test 3</u> Cool rail in ambient laboratory temperature after heating one side with angled heaters.

Test 3 used the same configuration as Test 2 but first heated the rail to 55°C. Temperature readings were logged as the rail cooled back down to ambient laboratory temperature.

<u>Test 4</u> Heat one side with angled heaters with wind chill on other side.

Test 4 used the same configuration as Test 2 but subjected the side of the rail opposite the heaters to wind chill. This was achieved by opening the test facility doors, achieving a wind chill between zero and five degrees Celsius.

<u>Test 5</u> Heat both sides with angled heaters placed at end of rail.

Test 5 reconfigured the rail and heaters so that the angled heaters directed radiant heat longitudinally along the rail from one end. Figure 4 shows the rail and heater configuration.

Figure 4 Test 5 rail and heater configuration.

The radiant heaters were dual filament radiant heaters rated at 3kW per heater. The dimensions of the heaters and the positions of the heaters and rail for the various configurations are as follows:

Width of pair of heaters = 1010 mm.
Element width = 330 mm.
Rail underside height from ground = 590 mm.
Lower heater element = 685 mm from ground with heater vertical.
Upper heater element = 885 mm from ground with heater vertical.
Lower heater element = 1010 mm from ground with heater at 45^{o}.
Upper heater element = 1170 mm from ground with heater at 45^{o}.
Elements = 430 mm from web for vertical heating.
Element centreline was aimed at web centre when one element heating.
Elements centreline was aimed at web centre when both elements heating.

2.2 Thermometer Comparison

Eight different new thermometers, either designed for rail use or potentially suitable for rail use, were evaluated against the data-logged thermocouple readings for accuracy and also compared for their usability. Generic feature and accuracy details of the eight thermometers are given in Table 2. Thermometer readings were taken at locations close to the surface mounted temperature sensors during Test 2. At least nine sets of readings were recorded. Figure 5 shows five contact thermometers on the test rail, Figure 6 shows the sixth contact thermometer and Figure 7 shows the two non-contact infrared thermometers. The emissivities of the infrared thermometers were set to 0.95 for testing and readings were taken on the oxidised surface of the web.

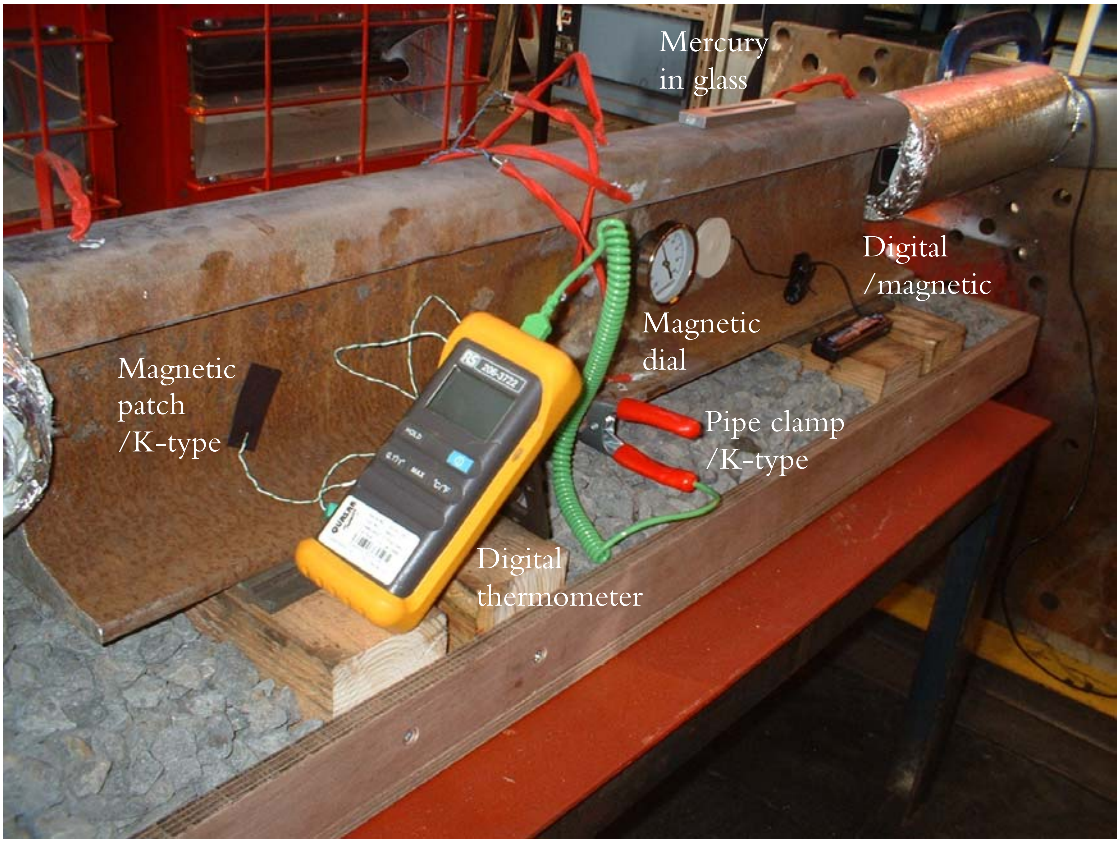


Figure 5 Five contact thermometers on test rail.

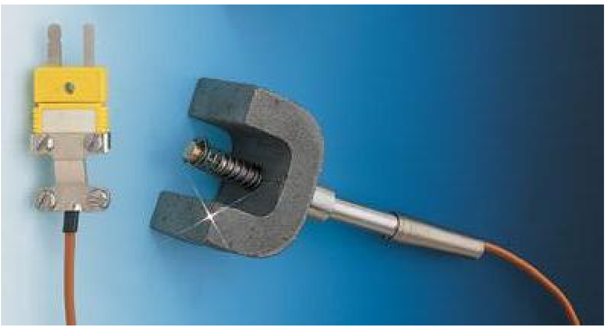


Figure 6 U-shaped magnet K-type thermocouple.

No.	Description	Range (Celcius)	Resolution (Celsius)	Accuracy (Celcius)	Accuracy at 55°C (Celsius)	Attachment Method	Price Index
1	Hand held non-contact infrared thermometer in a pen style housing.	-20 to +500	0.1	larger of ±1 degree or ±1% of reading	±1	Non-contact (Emissivity adjustable 0.3 to 1.0)	5.4
2	Hand held non-contact infrared pistol thermometer with data logging capability.	-32 to +600	0.1	larger of ±1 degree or ±1% of reading	±1	Non-contact (Emissivity adjustable 0.1 to 1.0)	8.9
3	Bi-metallic strip thermometer with circular dial display	-30 to +60	1	±1	±1	Magnet	1.0
4	Mercury in glass thermometer set in aluminium block	-20 to +50	1	±1	±1	Rest on horizontal surface	1.4
5	Digital/magnetic rail thermometer (sensor type not specified - possibly K-type thermocouple).	-50 to +70	0.1	±1 (estimate)	±1 (estimate)	Magnet	1.0
6	Hand held industrial digital thermometer used with pipe clamp K-type thermocouple	-50 to +150	0.1	±(0.2% of reading +1 degree)	±1.11	Similar spring-loaded clamp to a crocodile clip	2.5
7	Hand held industrial digital thermometer used with flexible magnetic strip K-type thermocouple	-50 to +100	0.1	±(0.2% of reading +1 degree)	±1.11	Magnet	2.1
7	Hand held industrial digital thermometer used with U-shaped magnetic K-type thermocouple	-50 to +1300	0.1	±(0.2% of reading +1 degree)	±1.11	Magnet	1.3

Note: Nos. 6, 7 and 8 use the same digital thermometer (display).

Table 2 Generic features of thermometers tested.

Figure 7 Two non-contact thermometers used on test rail.

3 Results and Analysis

This section presents the thermometer comparisons first, followed by the rail temperature behaviour results and analysis. The findings on correlating surface measurements with bulk rail temperature have relevance to the thermometer comparisons in that some types of thermometer can only be used on some surface locations.

3.1 Thermometer Comparison

Thermometer readings were taken at at least nine temperature intervals and compared to the data-logged values from adjacent thermocouples. Each thermometer's readings were correlated with the corresponding datalogger readings. Table 3 summarises these correlations. For practical purposes, the accuracy of the data-logged thermocouples and all the thermometers is taken as $\pm 1^{\circ}C$, therefore all are compared on the basis of the same accuracy.

Thermometer T	Datalogger values vs. Thermometer values Correlation	R-Squared Value of Correlation
1 (Infrared pen)	1.1 x T - 2.3	1.0
2 (Infrared pistol)	1.0 x T + 0.4	1.0
3 (Magnetic dial)	0.9 x T +2.5	1.0
4 (Mercury in glass)	0.9 x T + 2.8	1.0
5 (Digital/magnetic)	0.8 x T + 2.7	1.0
6 (K-type pipe clamp)	0.9 x T + 0.7	1.0
7 (K-type magnetic patch)	0.4 x T + 7.7	0.9
8 (K-type U-magnet)	0.9 x T + 1.1	1.0

Table 3 Thermometer vs. datalogger correlations.

The quality of the correlations summarised in Table 3 is that of the overall fit of each set of thermometer readings to the data-logged readings. However, these do not reveal underlying trends in the differences between the thermometers' readings and the data-logged readings. The process of fitting a line to the data using the Least Squares method (Appendix 2) tends to average out positive and negative differences, therefore a gradual trend, for example from a large positive error to a large negative error, would not be revealed. The differences between the thermometer and datalogger readings were therefore calculated and plotted to show these trends. Each difference is calculated as follows:

difference = thermometer reading - datalogger reading.

3.1.1 Infrared pen

Figure 7a indicates that the infrared pen readings were within a band of approximately ±2°C from the data-logged readings. However, a consistent trend is evident across the temperature range in that the infrared pen readings start off lower and gradually rise to become larger than the data-logged readings.

In terms of usability, this instrument is relatively small. Therefore it is difficult to set and adjust, particularly if the user is wearing work gloves, due to the small buttons. The digital display is also quite small and is not backlit.

The laser sight's dot is ~1 cm to the right of centre of the target area (manufacturer's data) but users intuitively use the dots location as the centre - this may lower the accuracy of readings if a target area consequently includes a mixture of background and intended target. In addition, distance from the target area must be within specification to avoid this type of inaccuracy (calibration distance is 300 mm with nominal target area diameter of 38 mm). It is possible that users would assume that temperature is measured over the area of the dot.

Although emissivity is adjustable, this operation requires a sequence of three buttons. This sequence is different to that used to change other settings. A fixed emissivity (of 0.95, for dark surfaces) was used in the tests as this would be the most practical approach from the point of view of use on track.

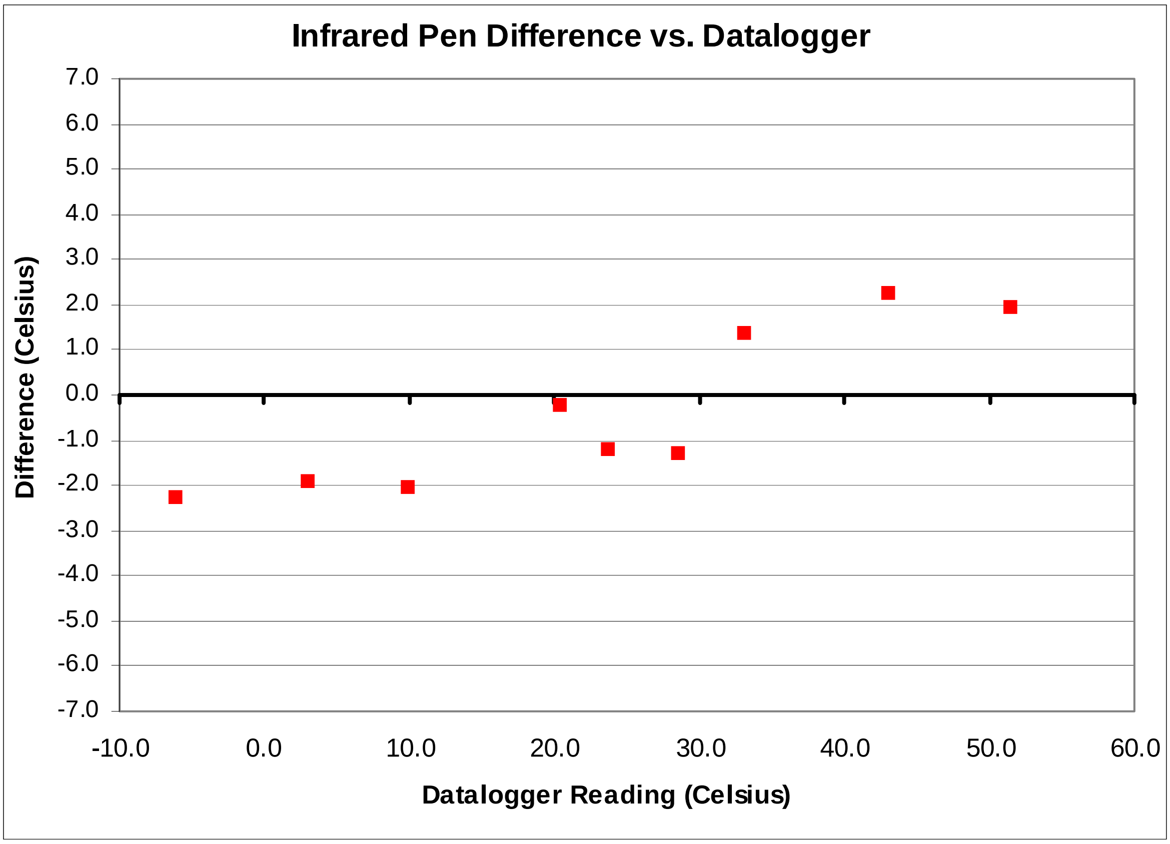


Figure 7a Plot of differences between infrared pen and datalogger.

3.1.2 Infrared pistol

Figure 7b indicates that the infrared pistol readings were within a band of approximately +2°C from the data-logged readings. The differences are much more consistent across the temperature range than those for the infrared pen, with only a slight trend towards larger differences with increasing temperature.

A fixed emissivity of 0.95 was used in testing and readings were recorded only for the web. The readings were found to vary significantly with the degree/age/texture of the oxidised web surface, typically by up to 3°C but across recently oxidised areas by up to by 7°C. The readings were also influenced by moisture on the surface.

In terms of usability, this instrument is reasonably user friendly and easy to use once set up (emissivity is set to the desired value by mode selection and scrolling up or down the available range). It has a readable, informative, backlit digital display. It has the capability to log up to 12 readings.

The infrared pistol has a smaller target area than the infrared pen - calibration distance is 300 mm with nominal target area diameter of 24 mm. Its laser sight's dot is also centred in the target area. It is possible that users would assume that temperature is measured over the area of the dot.

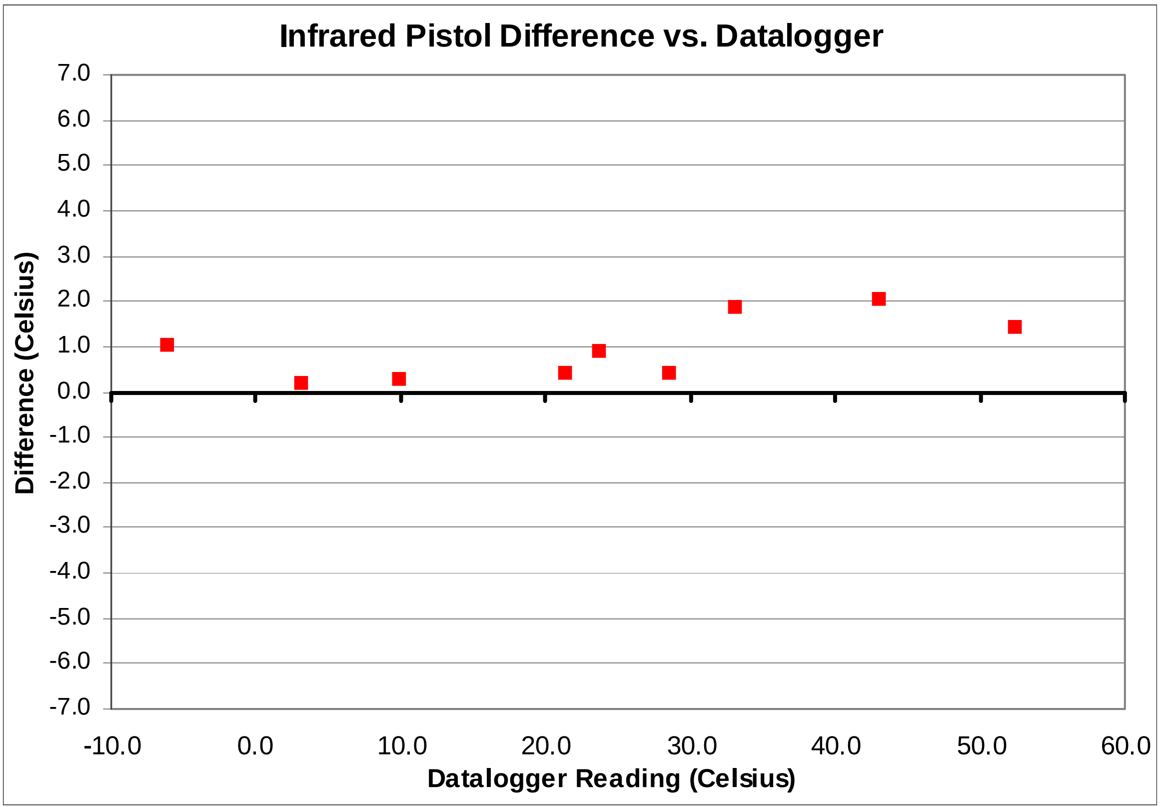


Figure 7b Plot of differences between infrared pistol and datalogger.

3.1.3 Magnetic dial

Figure 7c indicates that the magnetic dial thermometer's readings were within a band of approximately ±1°C from the data-logged readings, except for at the lowest and highest readings where the differences were +5°C and -3°C different, respectively. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is much less significant if one excludes the differences at the lowest and highest readings.

This thermometer is a simple instrument with the magnet providing a strong attachment to the rail surface. Its mating surface is flat and the test results were obtained with it attached to the web, which is an almost flat surface on CEN60E1 (BS113A has a flat web). The accuracy with which the dial is read varies with angle of view - the inaccuracy would vary with distance but could be degrees rather than fractions of a degree. The user must look directly at the dial from a perpendicular viewpoint for maximum accuracy of reading. This requirement is likely to make it difficult to read when used on the web on track - the user's eyes would have to be almost at ballast level to look perpendicularly at the dial.

The alternative of using it on the foot (as permitted say in RT/CE/S/011 when measuring temperature as part of stressing CWR), would make it much easier to read accurately but the foot has a concave upper surface (both CEN60E1 and BS113A) which prevents flush contact with the thermometer. In tests on the foot, the magnetic dial thermometer consistently displayed temperatures five to eight degrees lower than the mercury in glass, K-type pipe clamp and data-logged thermocouples. These differences also tended to increase with temperature.

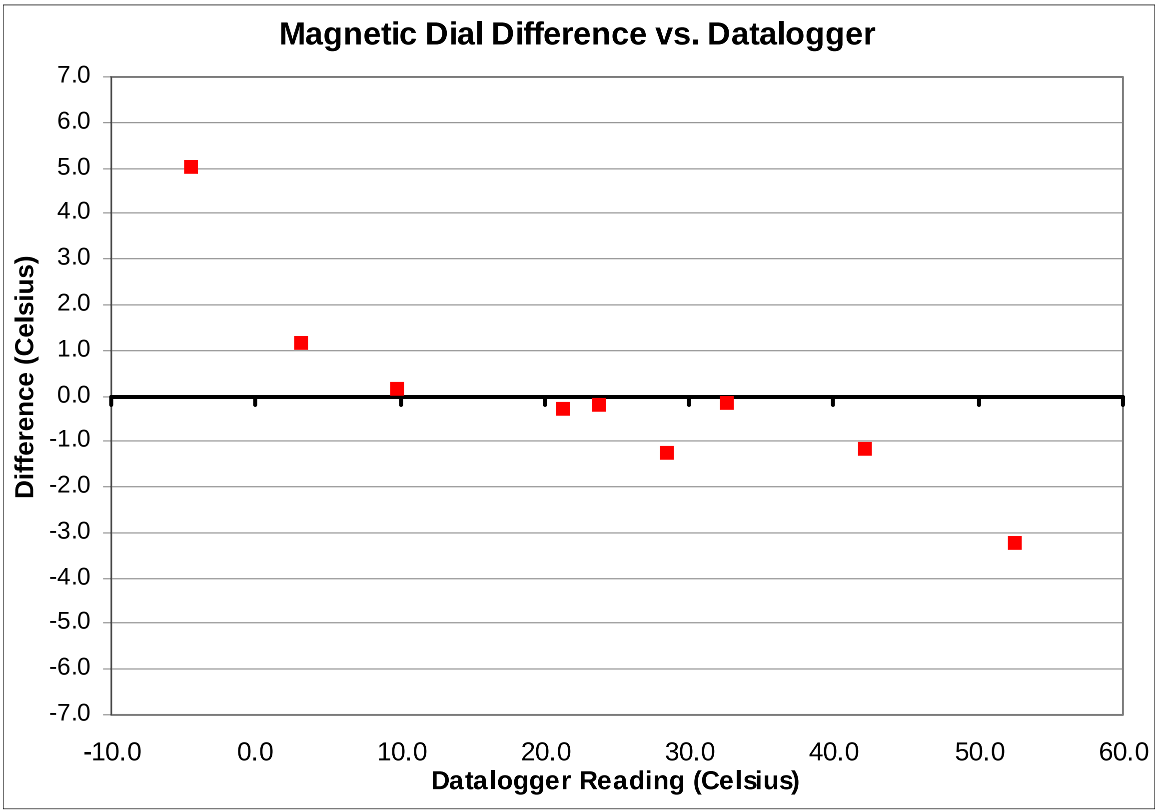


Figure 7c Plot of differences between magnetic dial and datalogger.

3.1.4 Mercury in glass (in aluminium block)

Figure 7d indicates that the mercury thermometer's readings were within a band of approximately +4 to -1°C from the data-logged readings. Interestingly, if the differences at the lowest and highest readings are excluded then this band reduces to approximately +2 to +1°C. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is much less significant if one excludes the differences at the lowest and highest readings. Note that the mercury thermometer's specified upper limit is 50°C.

This thermometer is also a simple instrument. It can only be used on horizontal (or near horizontal) surfaces as it has no means of positive attachment to the rail. The accuracy of reading it is also subject to the angle from which viewed, but to a much lesser extent than the magnetic dial i.e. the inaccuracy is more likely to be a fraction of a degree rather than a number of degrees.

The actual mercury in glass thermometer is mounted in an aluminium block and this must be allowed to equalise in temperature with the rail before a reading is taken. The thermometer is also subject to direct influence from radiant heat sources - the protective wooden box in which the thermometer is supplied was used to shield it from the radiant heat during testing.

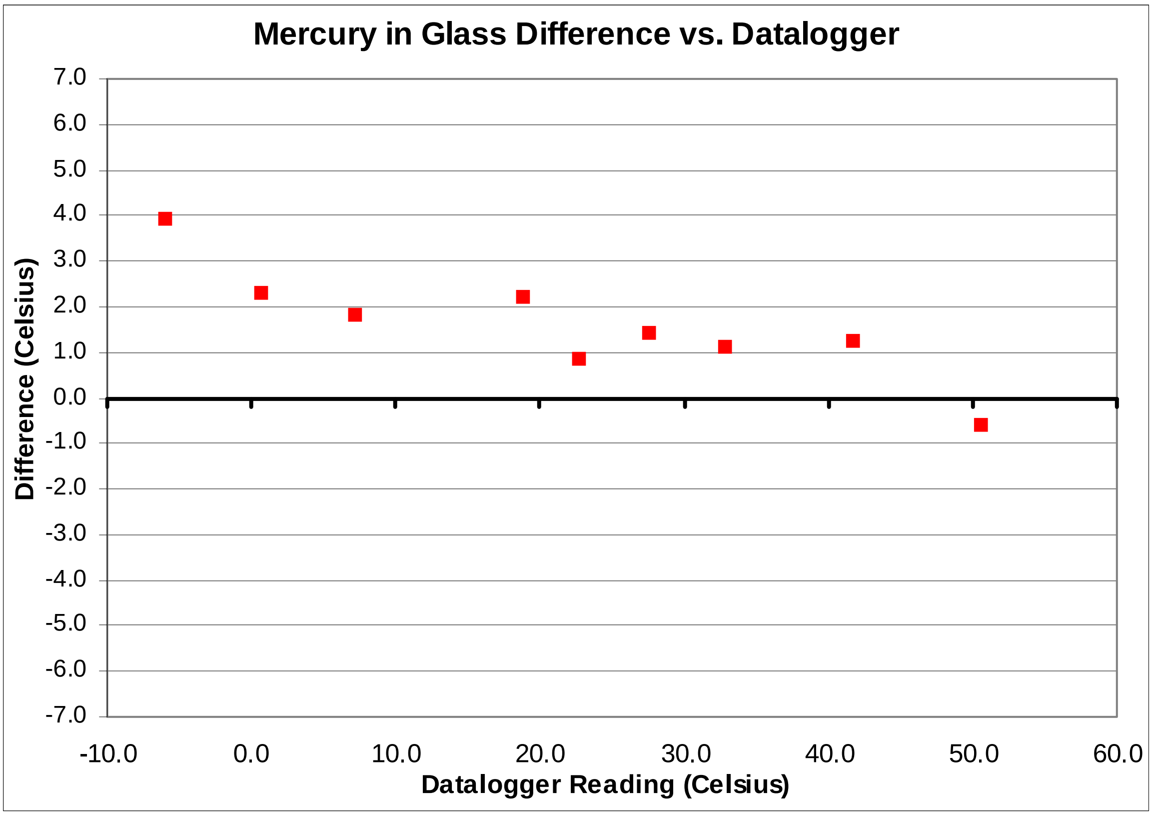


Figure 7d Plot of differences between mercury in glass and datalogger.

3.1.5 Digital/magnetic (K-type thermocouple)

Figure 7e indicates that the digital/magnetic rail thermometer's readings were within a band of approximately +3 to -6°C from the data-logged readings. If the largest difference is excluded then this band reduces to approximately +3 to -3°C. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is no less significant if one excludes the largest difference.

This digital/magnetic thermometer has a small magnetic disc to attach its sensor to rail. The manufacturer's specification does not describe the type of sensor but its size suggests a thermocouple. Its magnet is significantly smaller than that of the magnetic dial thermometer and provides a much less secure attachment. Testing suggested that the strength of attachment was borderline in terms of securing the sensor, for example light tension on the cable dislodged the sensor.

This thermometer is a small and lightweight instrument with small buttons. It is less easy to use with work gloves than larger instruments. It also measures ambient temperature with the digital display being switchable between rail and ambient. It has a digital clock and a backlight. Switching between modes during testing proved problematic, with the instrument needing to be reset by switching it off and on. This had to be achieved by removing the battery as it has no on/off switch.

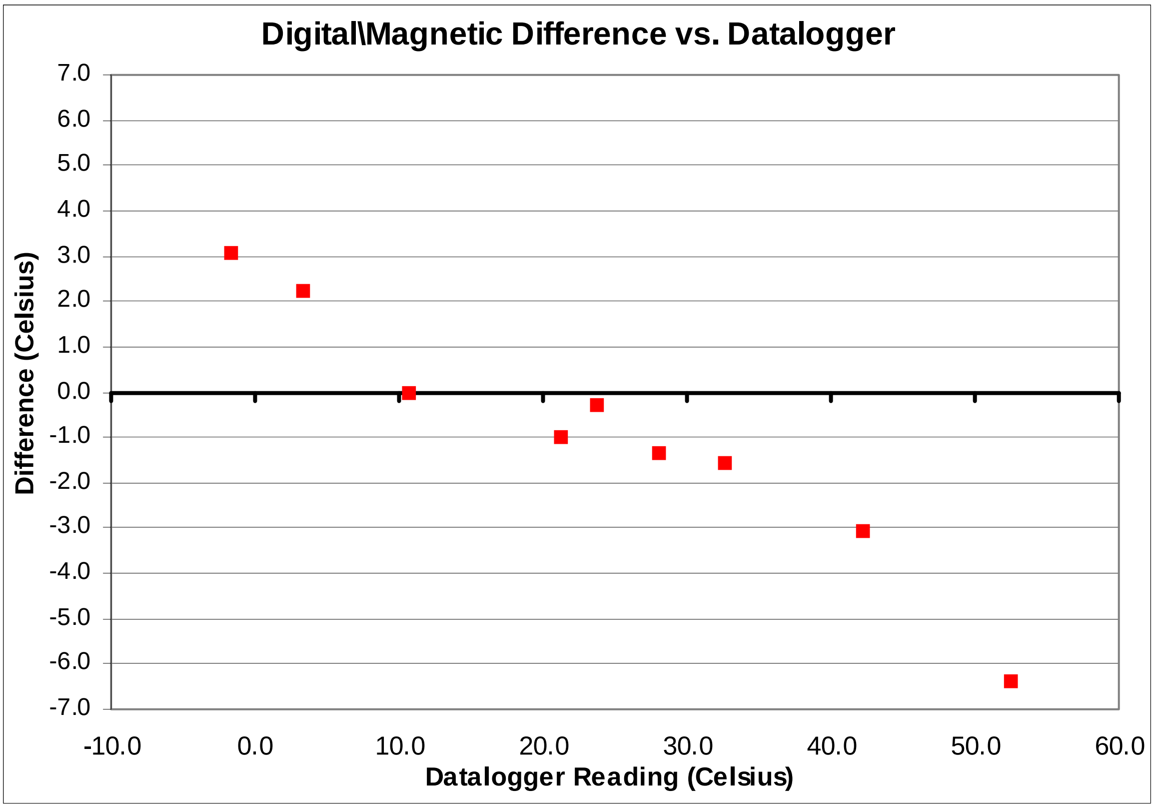


Figure 7e Plot of differences between digital\magnetic and datalogger.

3.1.6 K-type thermocouple pipe clamp

Figure 7f indicates that the readings from the K-type pipe clamp (used with the industrial digital thermometer) were within a band of approximately +1 to -4°C from the data-logged readings. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is consistent over all the readings.

The pipe clamp (similar to a crocodile clip in attachment) can only be used on the foot of the rail. Its attachment is very secure due to the strong spring within the clamp. The clamp was found during testing to be sensitive to wind chill, possibly because of the relatively large surface-to-mass ratio of its jaws (to which the thermocouple is attached) being unshielded/uninsulated. It gave readings 5 to 13°C lower than the surface mounted data-logged thermocouple when exposed to wind chill, with the difference increasing with temperature.

The digital industrial thermometer, set in a protective rubber surround, appears to be particularly robust. It was easy to operate, with large buttons each having just two functions - alternative button presses switch between functions.

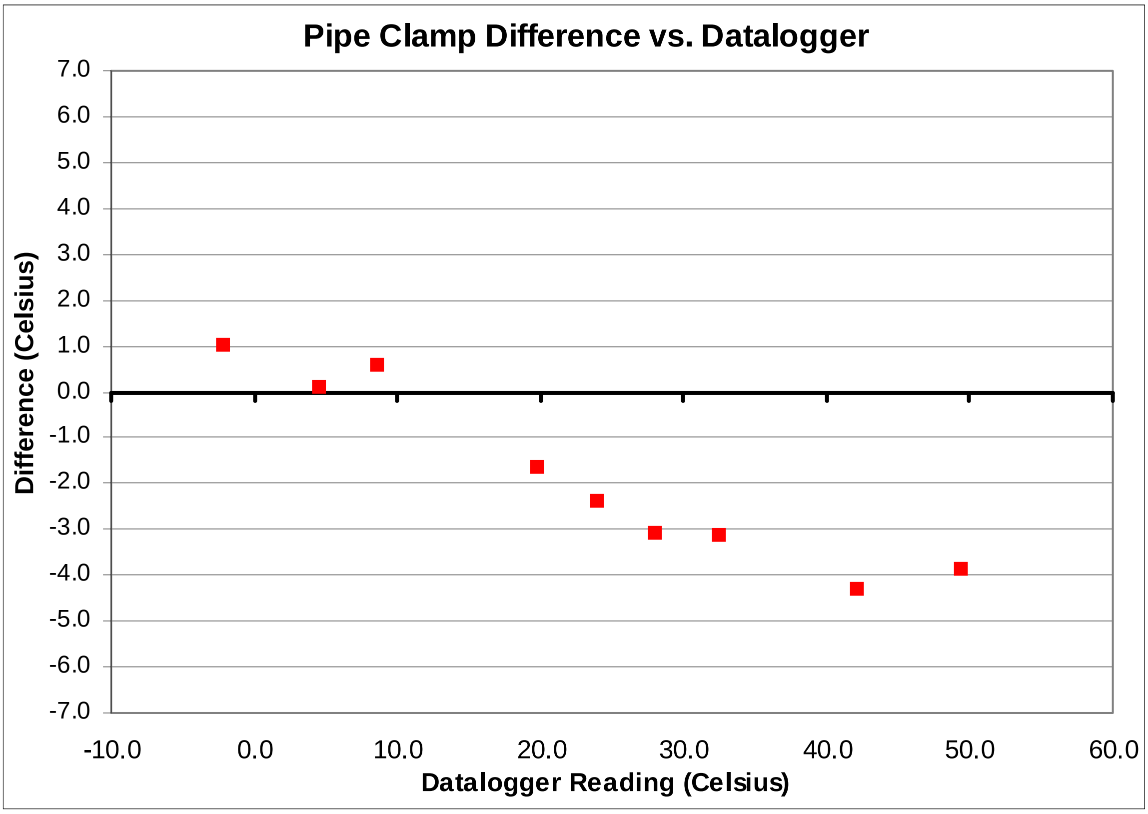


Figure 7f Plot of differences between K-type pipe clamp and datalogger.

3.1.7 K-type thermocouple magnetic patch

Figure 7g indicates that the readings from the K-type magnetic patch (used with the industrial digital thermometer) were within a band of approximately +8 to -27 °C from the data-logged readings. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is reasonably consistent over all the readings.

This magnetic patch suffers from a particularly weak magnet - it was difficult to secure it to any surface of the rail during testing. When attached, any disturbance of the cable immediately dislodged it.

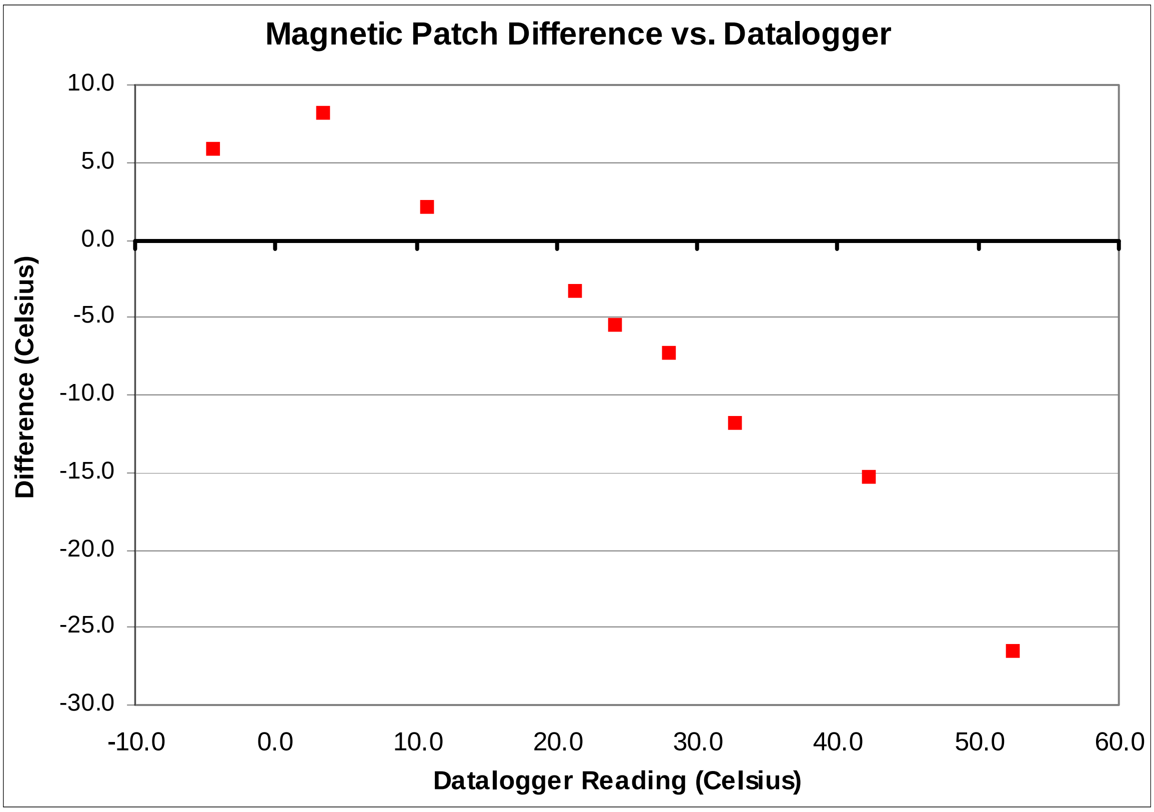


Figure 7g Plot of differences between K-type magnetic patch and datalogger.

3.1.8 K-type thermocouple U-magnet

Figure 7h indicates that the readings from the K-type U-magnet (used with the industrial digital thermometer) were within a band of approximately +3.5 to -5.5°C from the data-logged readings. The overall trend is that the thermometer readings start off higher and gradually decrease to become lower than the data-logged readings. This trend is reasonably consistent overall and is similar in direction to that for the other K-type thermocouples tested. However, if an approximate restricted range of 5 to 30°C is considered, then the readings are within a band of approximately +2 to -2°C with no significant trend.

The mass of the magnet temporarily affects the temperature of the rail in its vicinity - it must be allowed to equalise in temperature with the rail before obtaining a reading. The exposed surface of the magnet losing heat to the air possibly contributes to the larger negative differences with increasing temperature. Also, the small size of the flat, spring-loaded sensor head i.e. 5mm diameter, together with the freedom of the sensor to align itself at an angle other than 90° to the mating surfaces of the magnet, can result in incomplete contact whereby only part of the circumferential edge of the head is in contact with the rail surface. This permits the air temperature to affect the reading.

This magnetically attached (53 Newton pull force) thermocouple attaches securely to any surface location on the rail. It provides a robust, easy-to-use combination sensor and display when used with the digital industrial thermometer.

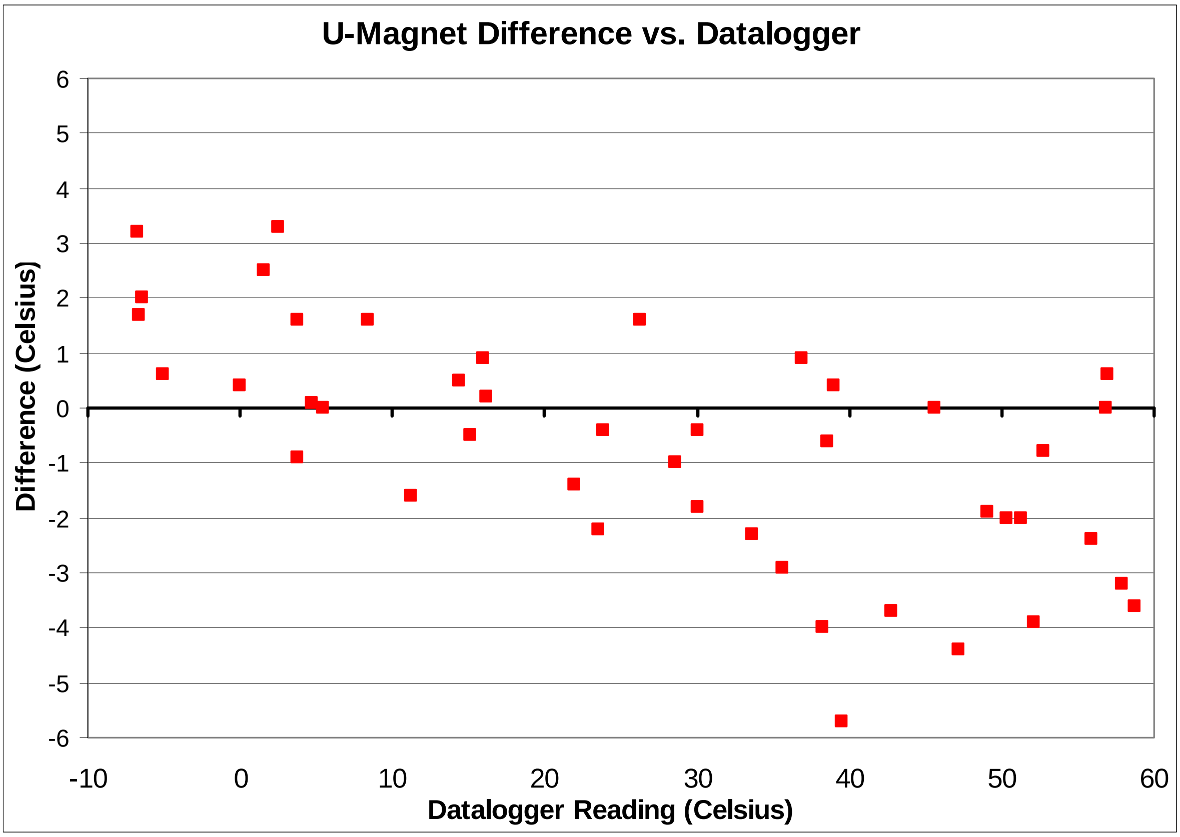


Figure 7h Plot of differences between K-type U-magnet and datalogger. This instrument was tested in an additional test, hence the increased no. of data points.

3.2 Rail Temperature Behaviour

Test 1 involved heating the rail from both sides. The rail is expected to expand uniformly (rather than bend sideways as expected if heated on one side only), therefore the expansion measured by the displacement transducers (LVDT's) reflects the bulk temperature rise of the rail. The results from Test 1 therefore permitted a calculation of change in bulk temperature from the measured expansion.

The results from the tests using heating on one side showed that the LVDT's would need to be positioned on the vertical centreline of the rail ends with a higher degree of accuracy than was possible by first mounting them within the heat shields, in order to reliably calculate bulk temperature from expansion. Consequently, the Test 1 results were first used to establish how best to determine/estimate bulk temperature from internal and/or surface temperatures.

The bulk temperature is an integral of the temperature throughout the test rail, therefore the average internal, average surface and average rail temperature (all internal and surface readings) were plotted and correlated against bulk temperature calculated from displacement. The following correlation was obtained between average internal temperature and bulk temperature and was subsequently used to calculate bulk temperature values from each of the other sets of test results.

Bulk Temperature = (1.0 x average internal temperature) + 1.3 $^{\circ}$C

Appendix 2 shows plots of measured expansion vs. bulk temperature; bulk, average surface, average internal and average rail temperatures vs. time; average internal versus bulk temperature (with the above correlation) and a plot comparing bulk temperature calculated from the correlation to that calculated from displacement.

Test 2 involved heating one side of the rail with the heaters angled down at 45° and moderated at eight temperature intervals to obtain steady state heat flows through the rail. Obtaining steady state heat flows through the rail is expected to remove effects of the rate of heating on test results, therefore the data logged during the steady states was used for analysis. Bulk temperature stayed within a 0.9°C band during each steady state (lasting four to five minutes each). Table 4 summarises the average temperature values obtained from the surface sensors during each steady state and the corresponding bulk temperatures (calculated from the average internal temperature using the above correlation from Test 1). Figure 8 shows a plot of these steady state averages.

Steady State	T2 Degrees Celsius *cool side of head*	T3 Degrees Celsius *hot side of head*	T4 Degrees Celsius *cool side of web*	T5 Degrees Celsius *hot side of web*	T6 Degrees Celsius *cool side of foot*	T7 Degrees Celsius *hot side of foot*	Calc. Bulk Temp. Degrees Celsius
1	17.9	19.0	18.9	18.7	18.4	19.8	20.9
2	22.9	24.1	23.9	23.7	23.1	24.9	25.8
3	27.5	28.7	28.5	28.3	27.4	29.5	30.5
4	31.9	33.3	32.9	32.7	31.9	33.9	35.2
5	36.2	37.7	37.8	37.7	36.3	40.6	39.8
6	40.7	42.3	42.6	42.7	41.2	46.2	44.4
7	45.0	46.7	47.2	47.2	46.2	51.1	49.2
8	49.8	51.4	51.9	51.9	51.3	55.8	54.1

Table 4 Test 2 Summary of steady states.

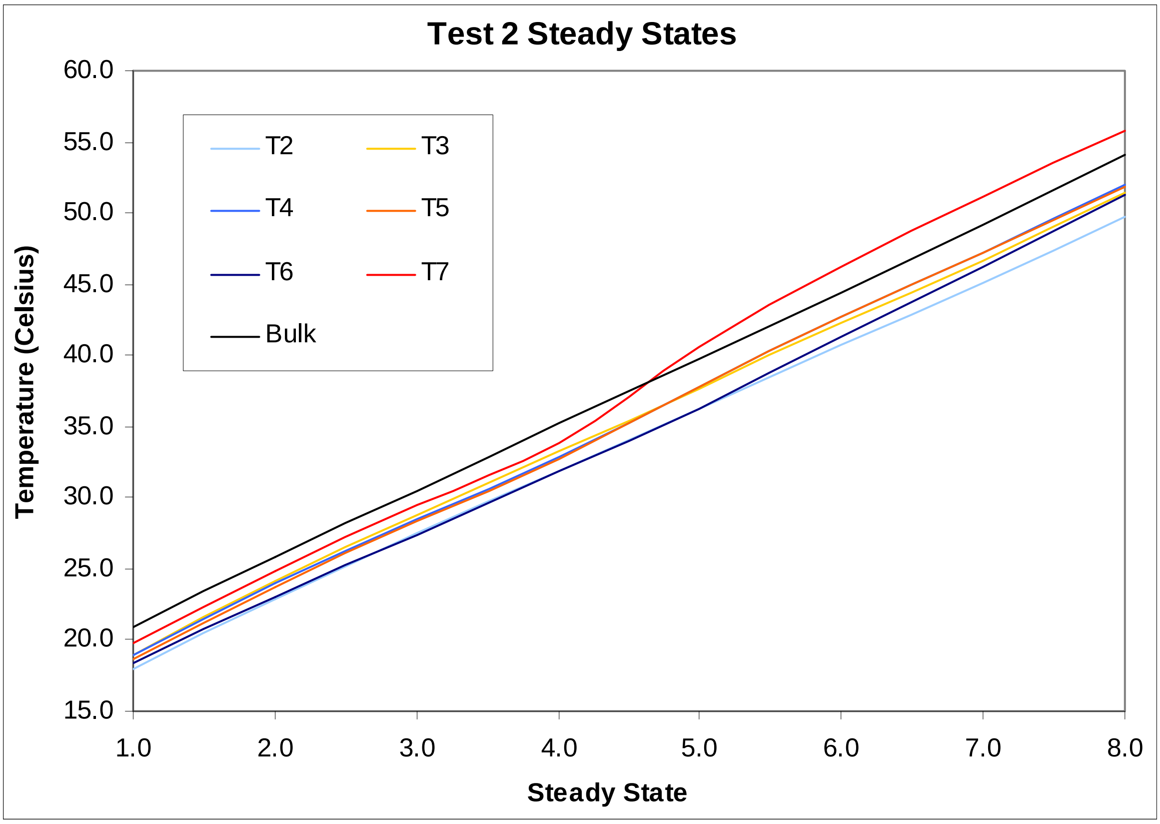


Figure 8 Test 2 plot of the steady state averages

Non-uniform heating, producing temperature gradients across a rail, is likely to be a more realistic (and difficult) situation, than uniform heating with no gradients, from which to try and relate surface to bulk temperatures. Correlations were obtained by plotting each of average head surface temperature, average web surface temperature, average foot surface temperature and average surface temperature against bulk temperature. The plots are shown in Appendix 3 with trend lines fitted and correlations shown. These correlations are summarised in Table 5.

Temperatures T	**Bulk vs. T Correlation**	**R-Squared Value of Correlation**
Average head surface temperature = (T2 + T3)/2	1.0 x T + 1.4	1.0
Average web surface temperature = (T4 + T5)/2	1.0 x T + 2.1	1.0
Average foot surface temperature = (T6 + T7)/2	1.0 x T + 3.1	1.0
Average surface temperature = (T2 + T3 + T4 + T5 + T6 + T7)/6	1.0 x T + 2.2	1.0
Note: An R-squared value closer to 1 indicates a better quality correlation.		
Table 5 Surface averages vs. bulk temperature correlations.		

The correlations from Test 2 were then tested against the results of Tests 1 (steady states), 3, 4 and 5. Each correlation was used to make a prediction of bulk temperature and these predictions were compared to the bulk temperature (obtained from the internal rail temperature). Table 6 summarises the R-squared values used to assess the quality of the fit of each prediction to the actual data (Appendix 2 explains R-squared). Appendix 4 contains the plots of predicted bulk versus bulk temperatures with trend lines fitted and correlations shown.

	Head Predicted Bulk Temperature	Web Predicted Bulk Temperature	Foot Predicted Bulk Temperature	Surface Predicted Bulk Temperature
Test 1	0.97	0.97	0.99	0.98
Test 3	1.00	1.00	1.00	1.00
Test 4	1.00	1.00	1.00	1.00
Test 5	1.00	1.00	1.00	1.00

Table 6 Summary of R-squared values for tests of bulk temperature predictions for Tests 1, 3, 4 and 5. Values are shown to two decimal places to show the small differences in Test 1.

As the bulk temperature is an integral of the temperature throughout the cross-section, one would expect that the more sensor locations included in a correlation with bulk temperature, the more accurate any prediction made using that correlation. The R-squared values in Table 6 nevertheless suggest that each of the head, web and foot averages (each using just two locations) correlate to the bulk temperature to a similar quality as the average of all six surface sensor readings. Figure 7 indicates that the foot temperature behaviour (see T6 and T7 in particular in Figure 8 and also R-squared values on plots in Appendix 3) is less consistent than the head and web behaviour. Observations during testing also indicated that temperature gradients were greatest across the foot, compared to those across the head and web.

4 Discussion and Recommendations

4.1 Thermometer Comparison

Individual examples of eight, different, new thermometers were tested. The findings therefore refer only to these individual examples. The findings also exclude consideration of possible degradation of thermometer performance during use on track and associated calibration issues. Other makes and models of each type of thermometer of varying and often better specification are available from suppliers. In sourcing those thermometers marketed specifically for rail use, it was noted that these tend to be at the lower cost, lower specification end of the market. This is likely to affect the overall performance of these instruments.

Testing the eight thermometers (or combinations of sensors and displays) revealed differing performances in measuring temperature and in terms of various factors affecting usability. Much of the evaluation of accuracy was based on the actual differences between thermometer readings and data-logged thermocouple readings (these thermocouples having been calibrated against a PRT with accuracy ± 0.1°C). Discussion here is followed by extraction of the key findings of relevance to measuring web temperature for the purposes of determining SFT and/or stressing CWR. Comments are also made which are relevant to the differing requirements of thermometer capability when used for monitoring rail temperatures in hot weather i.e. thermometers which exhibit decreasing accuracy in the upper half of the test range of -5 to +55°C may not be suitable for hot weather monitoring but may still be acceptable for use in stressing as this is limited to temperatures up to 27°C (or 32°C for crimp ended sleepers (RT/CE/S/011) and is most commonly done at low temperatures.

4.1.1 Infrared thermometers

The relatively narrow band of differences, and the band's consistency across the whole temperature range, suggest that the infrared pistol, or any similarly specified infrared thermometer, has the potential to be one of the most accurate of the types tested. If an automatically adjusting emissivity feature were added, this would be expected to move the difference band towards a zero centre. It would also cope with varying surface conditions, these being the most significant challenge to the accuracy of infrared readings, found during testing. Also, a simple cone attachment would ensure correct target size and distance by effectively converting the instrument to a contact thermometer. Emissivity adjusting instruments using contact cones are available. Alternatively, some infrared thermometers are available with a circle of laser dots which designate the target area.

4.1.2 Magnetic dial thermometer

The relatively large lowest and highest differences suggest that the magnetic dial thermometer has acceptable accuracy only when used well inside its specified range of -30 to +60°C, say from 0 to 40°C approximately. If restricted to this range, then its differences are within a 2°C band, centred on zero, suggesting that, over this range, it is the most consistently accurate thermometer tested. However, the accuracy with which the dial is read varies with the angle with which it is viewed by the user. An angled design would permit ease of reading when used on the rail web.

The magnetic dial thermometer attaches securely to the rail due to its relatively large magnet but requires a flat or nearly flat surface for good contact with the rail. Its contact area is relatively large (17mm diameter), providing good rail contact on the oxidised web surface. It showed significant inaccuracy when used on the concave rail foot, giving low readings particularly at higher rail temperatures where the effect of the lower air temperature on the incomplete contact was greater.

4.1.3 Mercury in glass thermometer

The mercury in glass thermometer also performed best on accuracy when used well inside its specified range of -20 to +50°C, say from 0 to 40°C approximately - the band of differences reduces to approximately +2 to +1°C for this restricted range. This thermometer can only be used on horizontal (or near horizontal) surfaces as it has no means of positive attachment to the rail. The accuracy of reading it is also subject to the angle from which viewed, but is more likely to be a fraction of a degree rather than a number of degrees as in the case of the magnetic dial thermometer. The actual mercury in glass thermometer is set in an aluminium block which must be allowed to equalise in temperature with the rail before a reading is taken. The uninsulated thermometer and block are also subject to heat transfer to the air and from direct radiant heat.

4.1.4 K-type thermocouple thermometers

The K-type pipe clamp (used with the industrial digital thermometer) attaches securely to the rail foot but can only be used on this location. It was found during testing to be sensitive to wind chill, possibly because of the relatively large surface-to-mass ratio of its jaws (to which the thermocouple is attached) which are unshielded/uninsulated. This sensitivity to ambient air conditions may contribute, partly or fully, to the trend of increasing negative differences with increasing temperature, even without direct wind chill. Additional insulation on the clamp may reduce this apparent sensitivity.

The coiled cable connecting the pipe clamp to the industrial digital thermometer is more compact and less prone to damage and accidental snagging that the straight cables of the digital/magnetic thermometer and the K-type magnetic patch. The industrial digital thermometer, appears particularly robust and is easy to operate. Overall, it scores highest of all the instruments on usability.

The K-type magnetic patch (used with the same industrial digital thermometer as the K-type pipe clamp) suffers from a particularly weak magnet. This lack of a secure attachment may have contributed to its relatively poor performance on accuracy by compromising the closeness of its contact with the rail surface.

The U-shaped magnetic K-type thermocouple attaches securely (53 Newton pull force) to any surface location on the rail. Used with the digital industrial thermometer, it is regarded as a robust, easy-to-use combination instrument. However, it only produced reasonable accuracy within an approximate restricted range of 5 to 30°C. The mass of the magnet was found to affect the temperature of the rail in its vicinity - it must be allowed to equalise in temperature with the rail before obtaining a reading. The uninsulated surface of the magnet is also suggested to contribute to increasing inaccuracy with increasing temperature. The small size of the flat, spring-loaded sensor head and the freedom of the sensor to misalign itself independent of the magnet, can result in incomplete sensor contact whereby only part of the circumferential edge of the head is in contact with the rail surface.

4.2 Key Points From Thermometer Comparison

In terms of accuracy and usability for measuring rail web temperature, the test results suggest the following points:

- An accuracy of ±1°C is regarded as a reasonable target to aim for in any individual measurement of rail temperature. Those thermometers that achieved a reasonably consistent 2°C band of differences to the data-logged readings are:
  - magnetic dial - its differences are within a 2°C band, centred on zero, within a range of 0 to 40°C approximately. Noting this range limitation, this is the best accuracy found in these tests.
  - infrared pistol - its differences are within a +1°C band up to 30°c approximately, thus indicating a potential for very accurate temperature measurement for stressing purposes. The significant caveat is the variability of the surface conditions affecting readings by up to 7°C during testing - an automatically adjusting emissivity would be expected to counter this sensitivity.

- A sufficiently strong method of attachment to the rail is required. A magnet of appropriate strength is found to work well, for example as fitted to the magnetic dial thermometer and the U-magnet thermocouple.

- A sufficiently close contact with the rail is required. A sensor with a relatively large contact area is found to work well, for example as fitted to the magnetic dial thermometer.

- A robust instrument is necessary for rail application. The industrial digital thermometer (used with the pipe clamp and U-magnet thermocouples) is regarded as the most robust instrument tested. The infrared pistol is second only to the industrial digital thermometer. Thermometers with hard and/or brittle cases such as the magnetic dial or the mercury in glass need care when handling and may be more easily damaged if accidentally dropped. They do however have advantage of being in one piece i.e. no cables. They also have the advantage of not requiring a power supply.

- Rail thermometers must retain their performance in relatively harsh conditions (compared to those in a laboratory). Network Rail standard RT/CE/S/011 currently requires that all thermometers are checked against a master thermometer at least once a year. Given that some thermometers may be more easily damaged than others, frequency of checking and/or calibration might usefully be tailored to the different types of thermometers in use. Calibration should be according to manufacturer's guidelines, where these are provided.

- Ease of operation is essential for a rail thermometer - it should be possible to simply attach the instrument (or its sensor) and repeatedly take readings. The magnetic dial thermometer and the industrial digital thermometer (used with the pipe clamp and U-magnet thermocouples) are among the better performing instruments overall which achieve this. These are two of the three types of instrument mentioned in RT/CE/S/011 (the third is mercury thermometers).

4.3 Rail Temperature Behaviour

Rail bulk temperature, at a particular longitudinal location, can be regarded as an integral of the temperature throughout the cross-section at that location. This suggests that the more points at that cross-section that temperatures are measured at in order to estimate bulk temperature, the more accurate the estimate will be. However, in terms of practical measurement of temperature on track, the fewer points requiring measurement the better.

Given that the bulk temperature predictions based on the head surface average, web surface average and foot surface average (each using two locations) are of similar quality to the prediction made from the surface average (using six locations), this suggests that bulk temperature at a given cross-section may usefully be estimated by taking no more than two temperature readings. In choosing between the head, web and foot, the following are considered:

- RT/CE/S/011 Continuous Welded Rail (CWR) Track Section 9.10 Measurement of Rail Temperature requires that thermometers shall be placed on (the shaded side of) the rail foot or web.
- The web was found to react to external temperature influences more rapidly than the head during testing.
- The foot temperature behaviour was observed to be less consistent than the head or web and the foot exhibited greater temperature gradients from hot to shady side during testing.
- Opposite sides of the web are more likely to have similar surface quality in track than opposite sides of the head which may be subject to flange contact and/or wheel contact on the gauge corner.

The web is therefore judged to be the best of the three locations for measuring the temperature. Given the more rapid reaction of the web to external temperature influences - the shaded side temperature was within 0.2°C of the hot side up to about 27°C and within 0.4°C from about 27°C to 55°C - it is considered practical to measure only the shaded side temperature as a good approximation of the web average temperature. Therefore, it is suggested that the bulk temperature at a given rail cross-section may usefully be estimated by measuring the temperature on the shaded side of the web, then applying the following correlation:

$$\text{Bulk temperature} = \text{Web (shaded side) temperature} + 2.1^{\circ}\text{C}$$

The difference in bulk temperature values between using this suggested method and the existing one in RT/CE/S/011 suggests that the existing method may be underestimating the bulk temperature by about 2°C, leading to stressing to a higher stress free temperature (SFT) than the intended target of 27°C. However, it is believed that the existing method is itself based on rail temperature measurements taken on the web, for example, measurements taken on the shady side of the web are regarded as an acceptable measure of the average section temperature in the British Railways Board report RR TM 013, An Analysis of Track Buckling

Risk by Hunt, G. A., 1994. This utilisation of web surface temperature as representing bulk rail temperature would have to be taken into account if implementing the above correlation.

Figure 9 shows an example comparison of the existing RT/CE/S/011 temperature measurement method and the bulk temperature found from the web average correlation. Test 4 data is used as the rail (foot in particular) had significant temperature gradients across it due to wind chill on the shaded side.

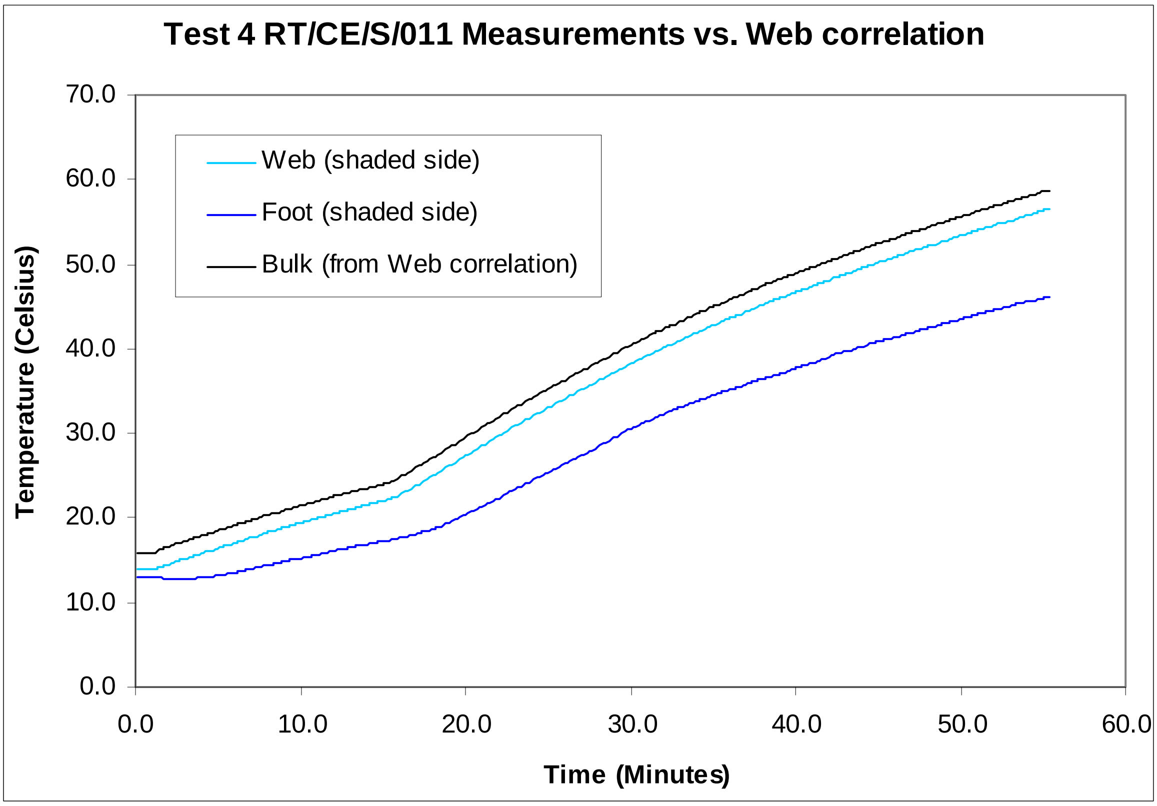


Figure 9 Comparison of rail temperatures measured using existing RT/CE/S/011 method and web average correlation from the present study's findings.

Appendices

CONTENTS

Appendix 1	Details of the eight thermometers tested. **(Removed to allow for wider circulation)**
Appendix 2	Test 1 Correlation between average internal and bulk temperature
Appendix 3	Test 2 Correlations between bulk and average surface temperatures
Appendix 4	Plots of predicted bulk versus bulk temperatures

Appendix 1
Details of the eight thermometers tested

(Removed to allow for wider circulation)

CONTENTS

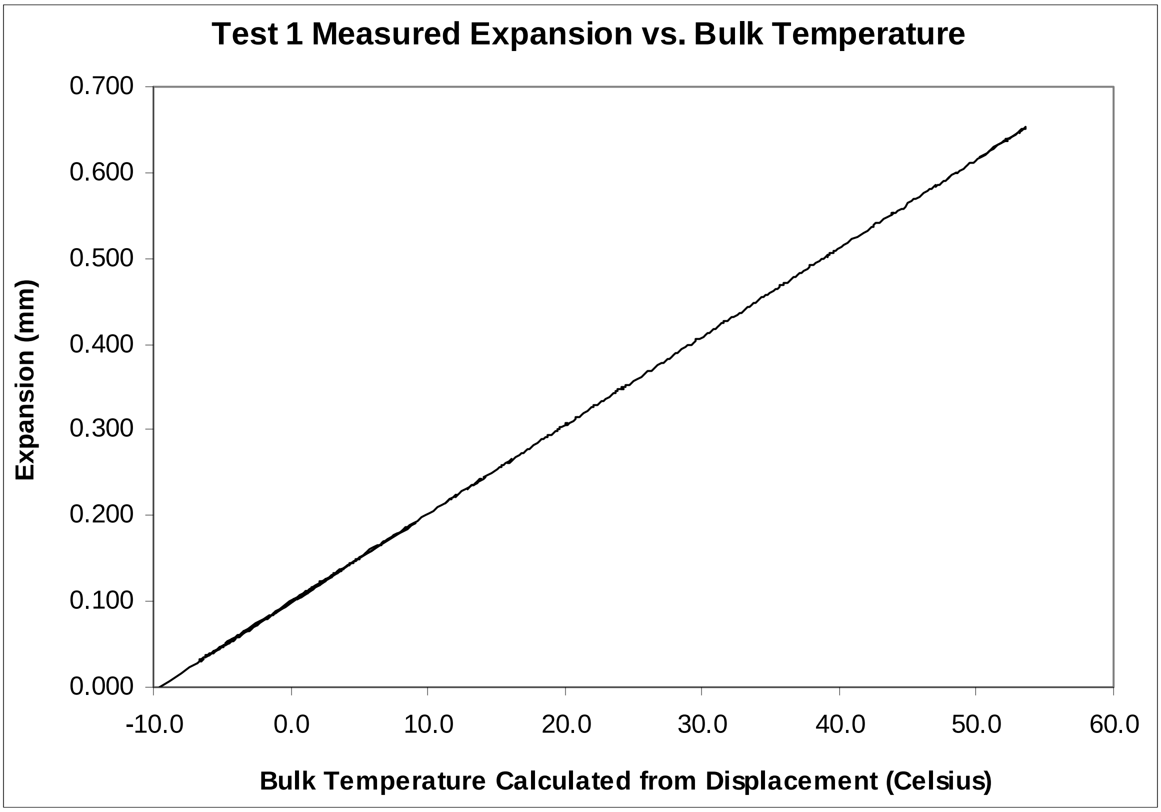
Details of the eight thermometers tested

Appendix 1 Table Removed to allow for wider circulation

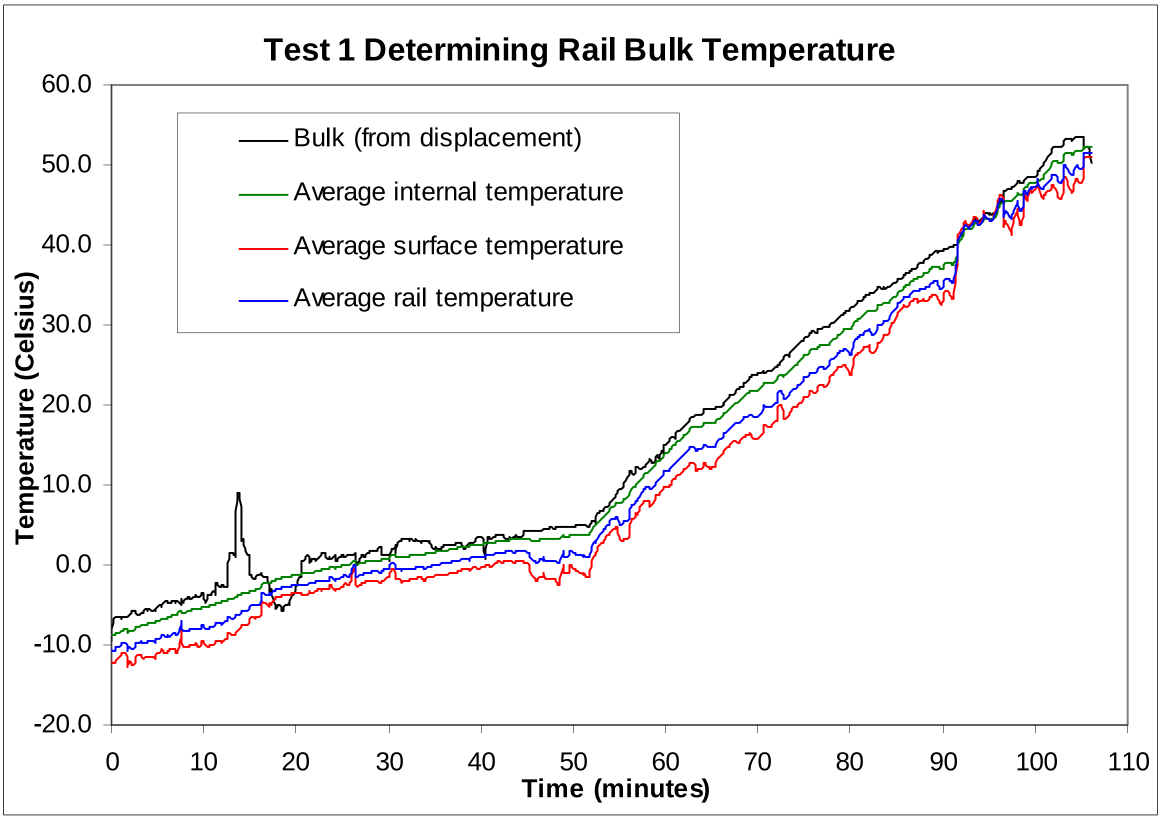
Appendix 2
Test 1 Correlation between average internal and bulk temperature

CONTENTS

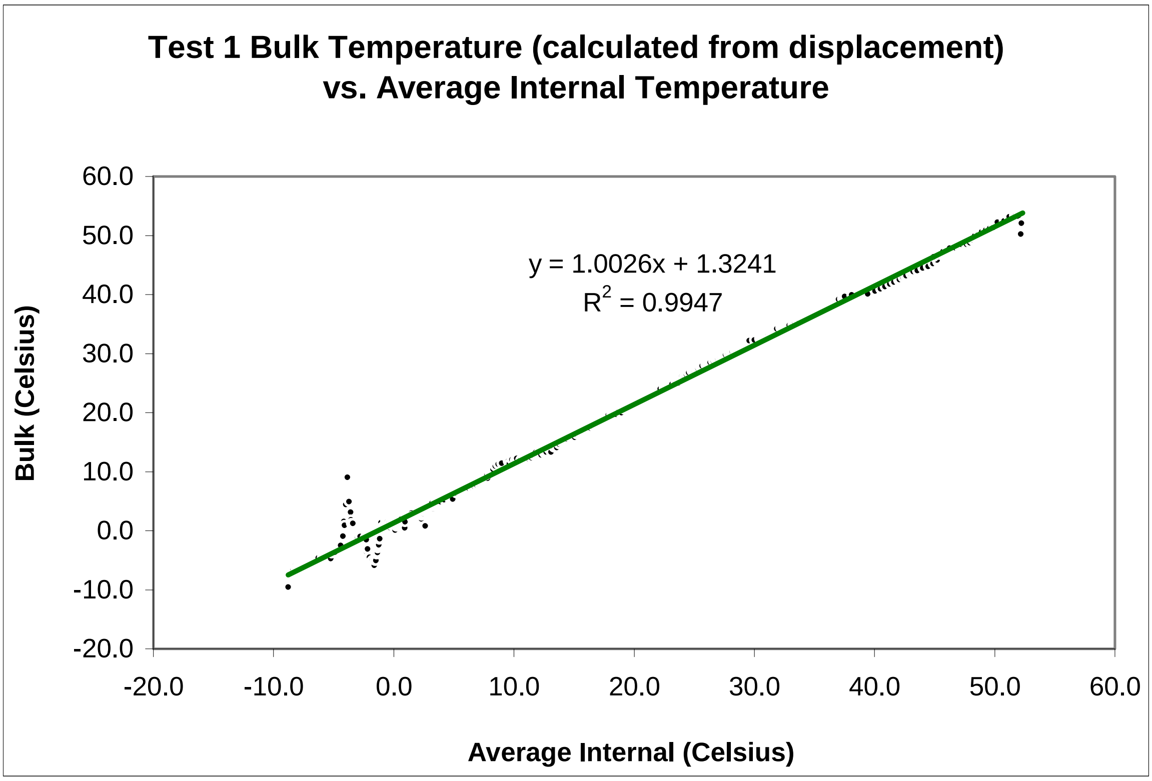
Test 1 Correlation between average internal and bulk temperature



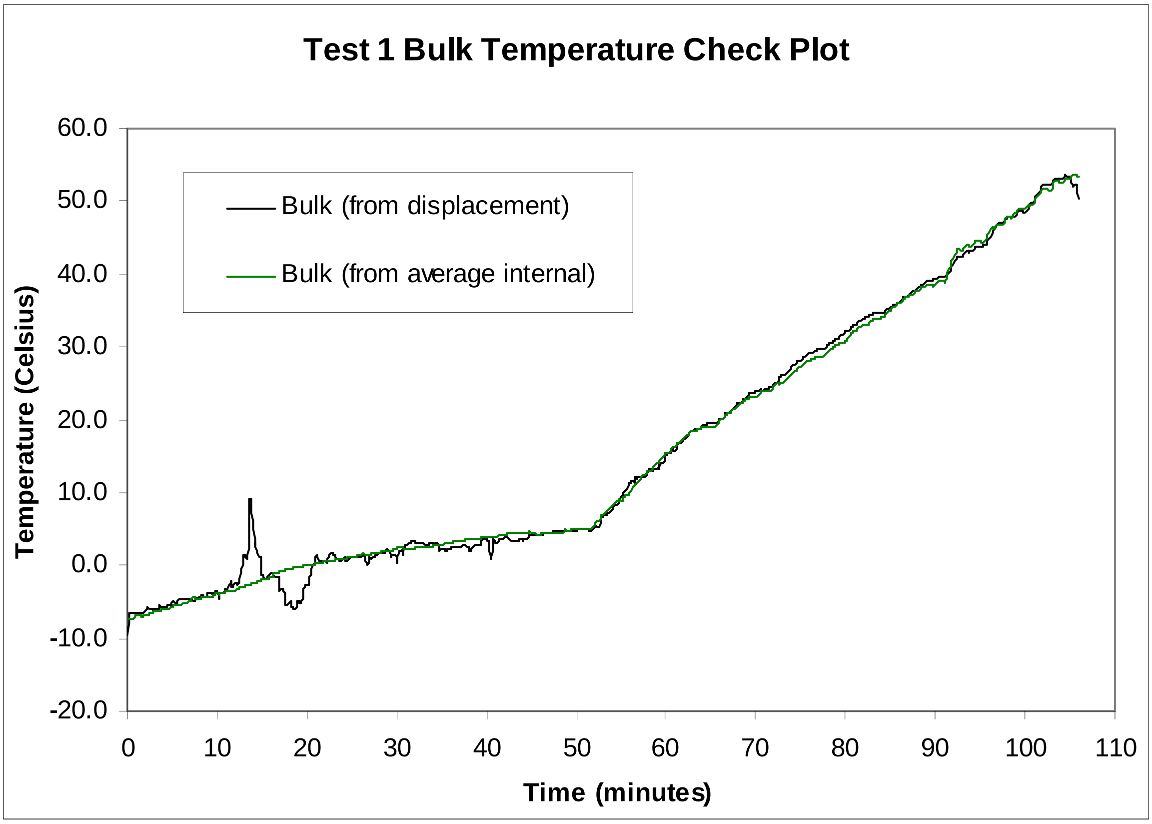
Test 1 Measured Expansion vs. Bulk Temperature
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Expansion (mm)
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Bulk Temperature Calculated from Displacement (Celsius)



Test 1 Determining Rail Bulk Temperature
Bulk (from displacement)
Average internal temperature
Average surface temperature
Average rail temperature
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
Temperature (Celsius)
0
10
20
30
40
50
60
70
80
90
100
110
Time (minutes)



Test 1 Bulk Temperature (calculated from displacement)
vs. Average Internal Temperature
y = 1.0026x + 1.3241
R2 = 0.9947
Bulk (Celsius)
Average Internal (Celsius)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0



Test 1 Bulk Temperature Check Plot
Bulk (from displacement)
Bulk (from average internal)
Temperature (Celsius)
Time (minutes)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
0
10
20
30
40
50
60
70
80
90
100
110

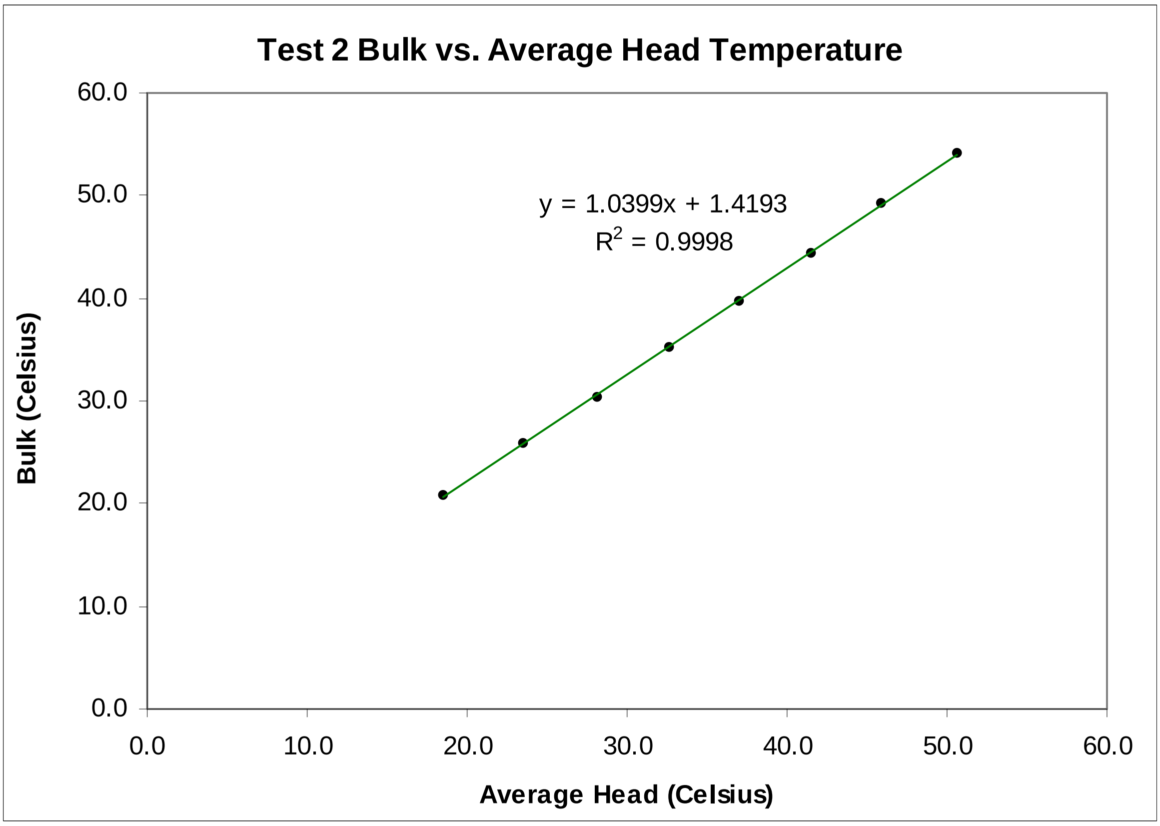
Explanation of R-squared

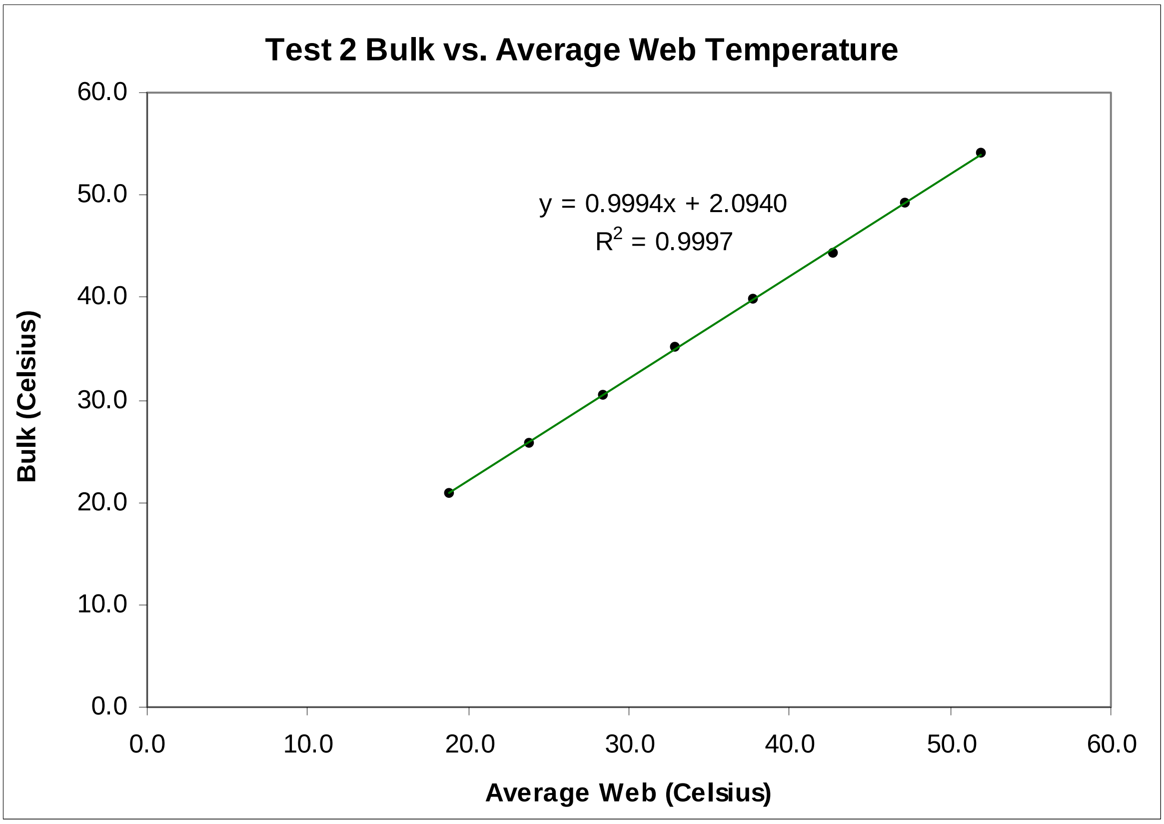
The correlation coefficient, R-squared, can be interpreted as the proportion of the variance in a data set (population sample) of one variable attributable to the variance in a data set (population sample) of a second variable, when the two sets of data are compared, typically by plotting one against the other. Its value ranges from zero to one, with zero indicating no linear correlation between the data sets and one indicating perfect linear correlation between them. In terms of fitting a trend line to a plot, as done using the Least Squares method in Microsoft Excel in this study, an R-squared value of one indicates a 'perfect' fit of the trend line to the data.

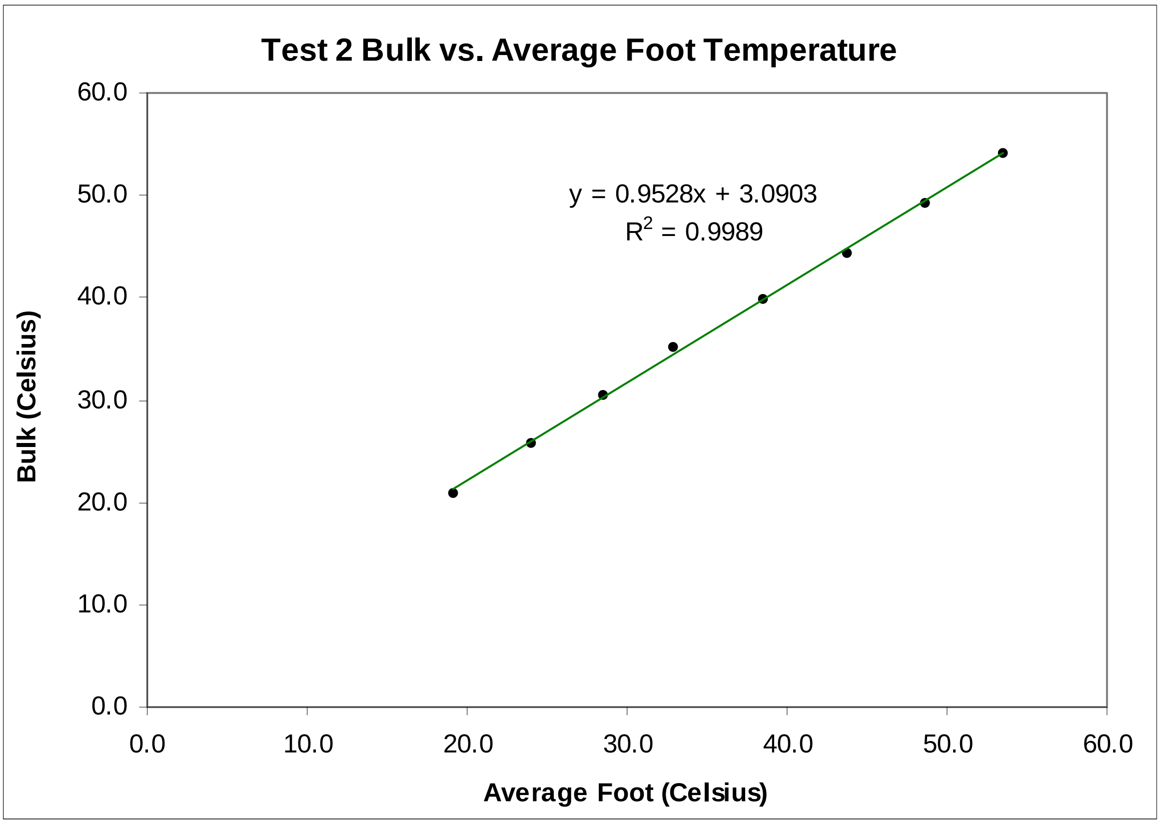
Appendix 3
Test 2 Correlations between bulk and average surface temperatures

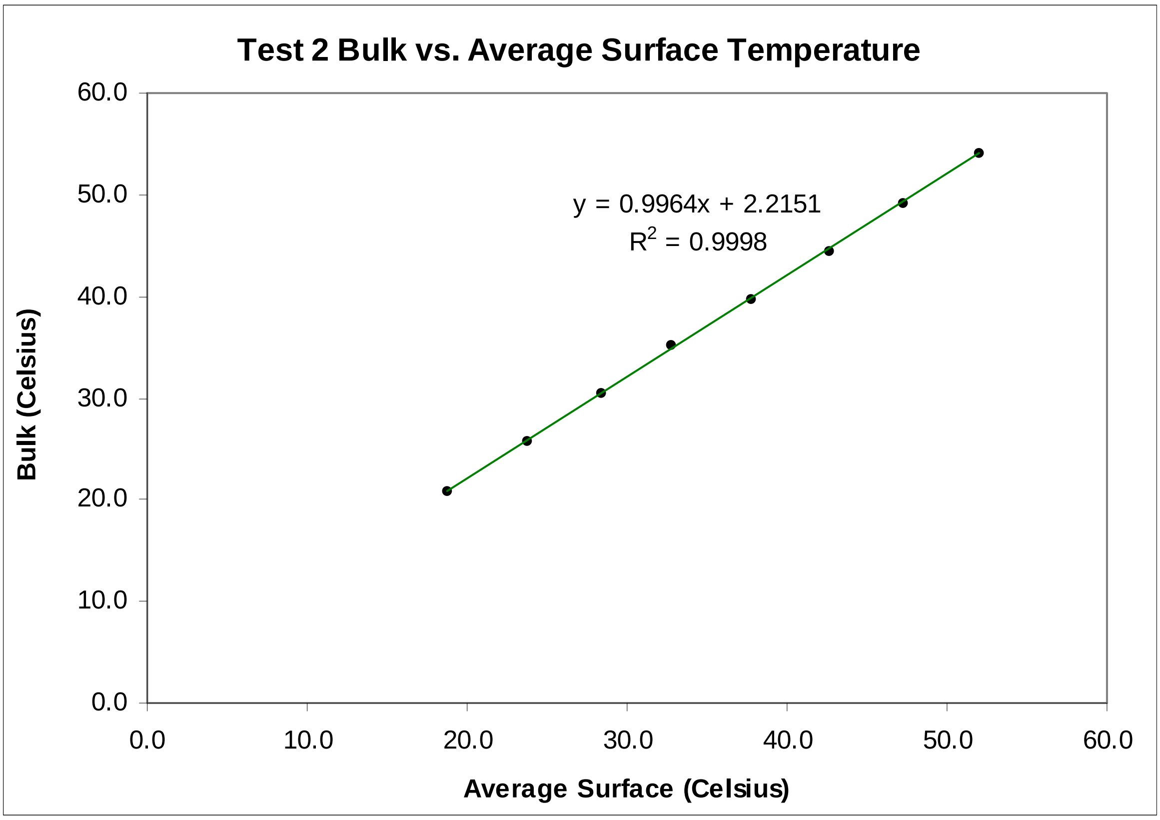
CONTENTS

Test 2 Correlations between bulk and average surface temperatures


Test 2 Bulk vs. Average Head Temperature
y = 1.0399x + 1.4193
R2 = 0.9998
Bulk (Celsius)
Average Head (Celsius)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0


Test 2 Bulk vs. Average Web Temperature
y = 0.9994x + 2.0940
R2 = 0.9997
Bulk (Celsius)
Average Web (Celsius)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0

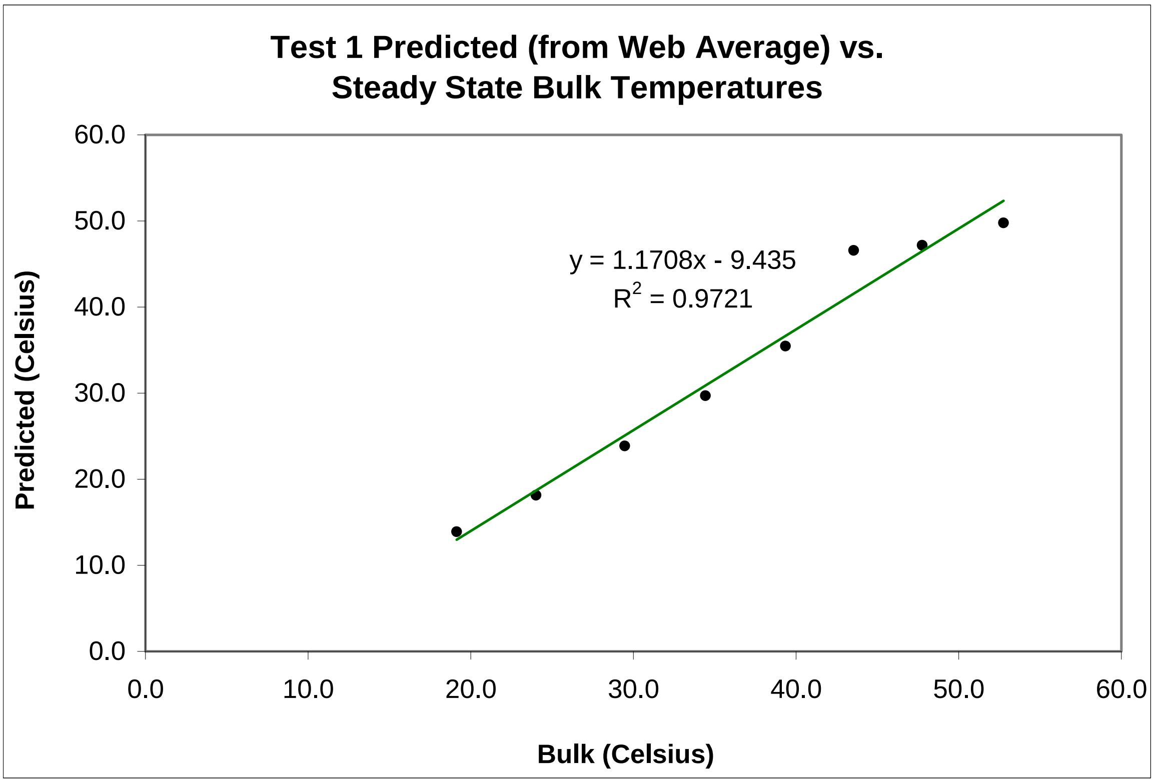

Test 2 Bulk vs. Average Foot Temperature
y = 0.9528x + 3.0903
R2 = 0.9989
Bulk (Celsius)
Average Foot (Celsius)
0.0
10.0
20.0
30.0
40.0
50.0
60.0

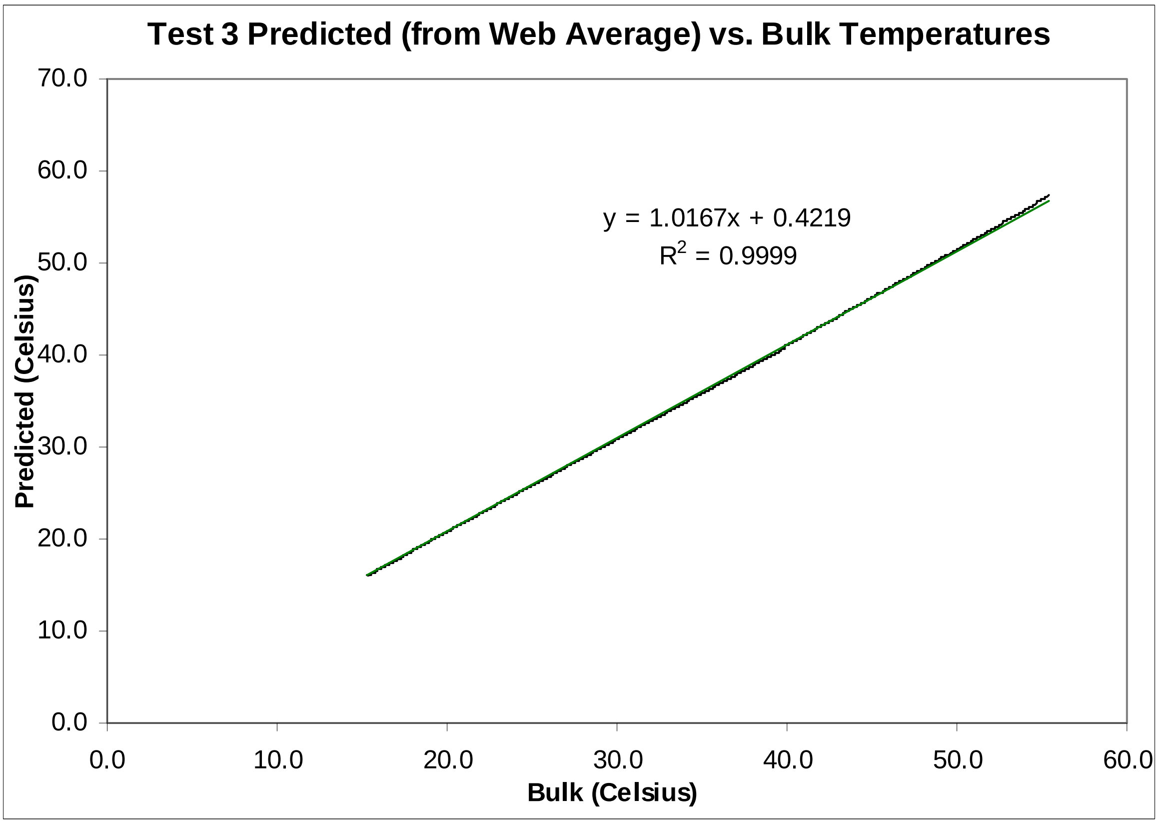

Test 2 Bulk vs. Average Surface Temperature
y = 0.9964x + 2.2151
R2 = 0.9998
Bulk (Celsius)
Average Surface (Celsius)
0.0
10.0
20.0
30.0
40.0
50.0
60.0

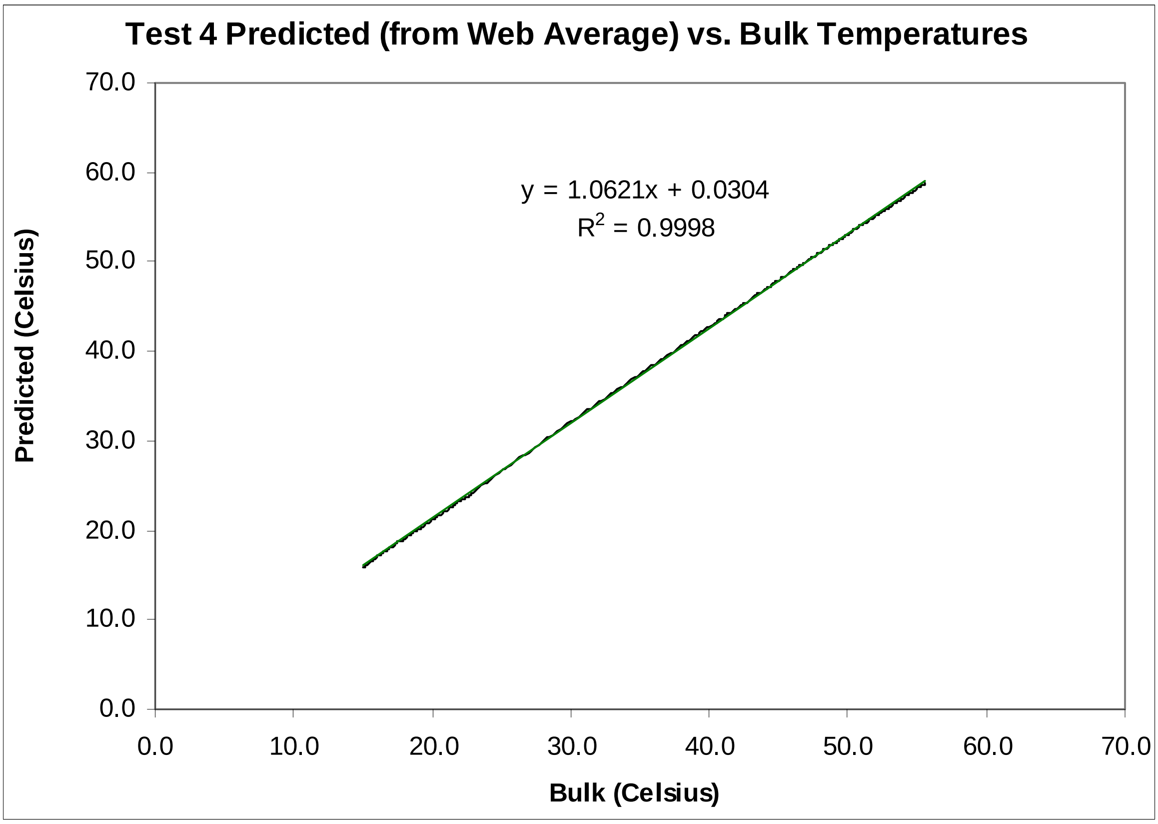
Appendix 4
Plots of predicted bulk versus bulk temperatures

CONTENTS

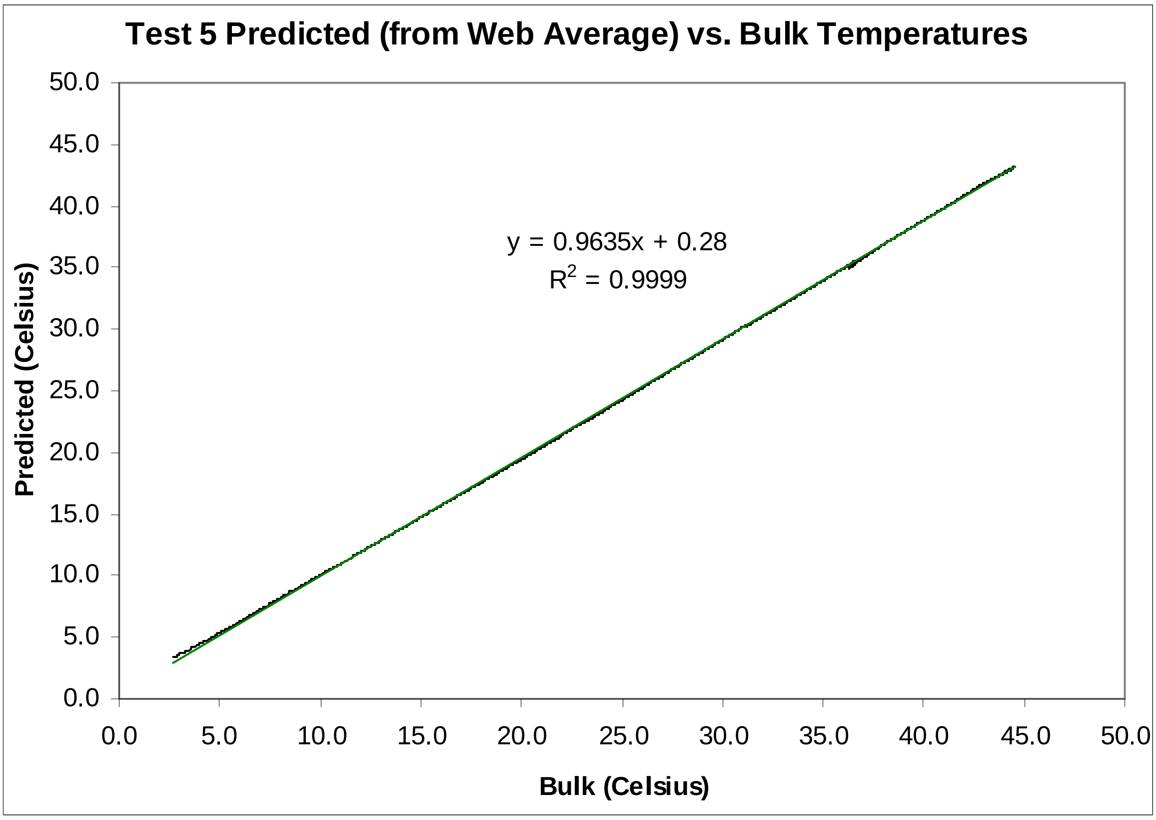
Plots of predicted bulk versus bulk temperatures


Test 1 Predicted (from Web Average) vs.
Steady State Bulk Temperatures
y = 1.1708x - 9.435
R^2 = 0.9721
Predicted (Celsius)
Bulk (Celsius)
0.0
10.0
20.0
30.0
40.0
50.0
60.0


Test 3 Predicted (from Web Average) vs. Bulk Temperatures
y = 1.0167x + 0.4219
R^2 = 0.9999
Predicted (Celsius)
Bulk (Celsius)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0



Test 4 Predicted (from Web Average) vs. Bulk Temperatures
y = 1.0621x + 0.0304
R2 = 0.9998
Predicted (Celsius)
Bulk (Celsius)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0



Test 5 Predicted (from Web Average) vs. Bulk Temperatures
y = 0.9635x + 0.28
R2 = 0.9999
Predicted (Celsius)
Bulk (Celsius)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0

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