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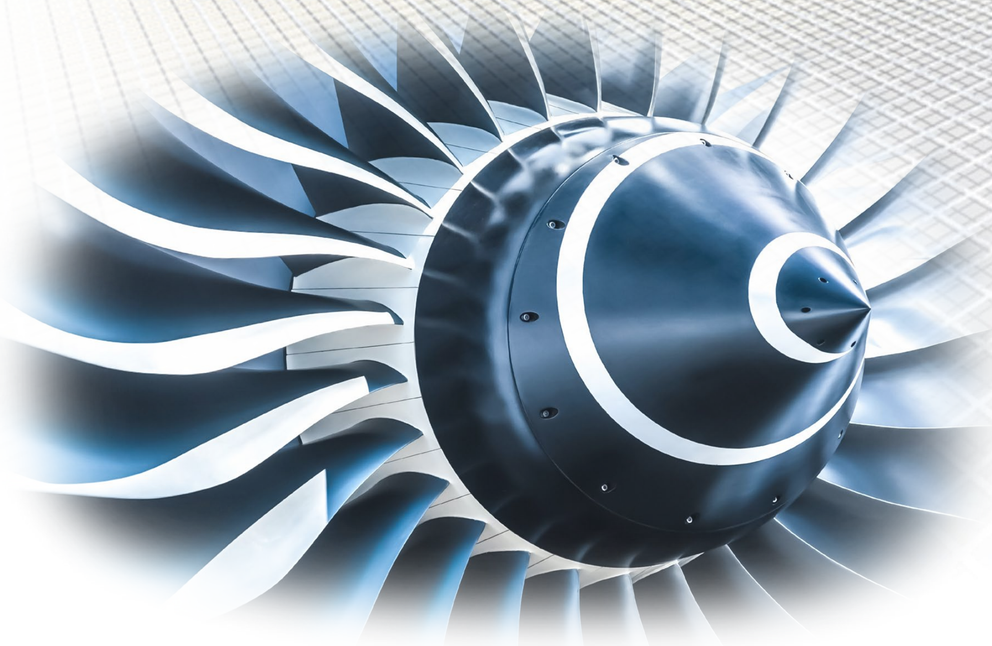

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LOW DRIFT TYPE K AND N MINERAL INSULATED THERMOCOUPLE CABLE FOR AEROSPACE APPLICATIONS

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Abstract

As a result of research conducted by the Department of Materials Science and Metallurgy at the University of Cambridge and tests conducted in the calibration laboratory at CCPI Europe Ltd, a new mineral insulated (MI) thermocouple cable has been developed for sensor manufacturing. The use of both type K and type N base metal thermocouple combinations under operational conditions during extended and/or high temperature conditions have historically been shown to have a limited life operation.

The test results on mineral insulated cable show that conventional type K mineral insulated thermocouple designs can maintain calibration limits and stay within IEC 60584 -1: 2013 class 1 and ASTM E230 special tolerances for a limited number of operations. However, when compared to the type K sensors, manufactured from the new designed mineral insulated cable, these new designs have been shown to maintain calibration values to meet both IEC 60584 -1: 2013 class 1 and ASTM E230 special tolerances for up to five times longer.

This new mineral insulated cable can allow type K and N thermocouples to work longer and at higher temperatures with significantly reduced drift, offering greater measurement confidence.

This paper will discuss how the new design will offer the opportunity for type K and type N MI thermocouples to work for longer and at higher temperatures under both continuous and cycling conditions with significantly reduced drift, giving increased confidence in measurement capability.

Introduction

Base metal thermocouples such as the type K (Nickel Chromium v Nickel Aluminium) and the type N (Nisil v Nicrosil) sensors have been, and continue to be, the most common thermocouple used by manufacturing industry for temperature measurement.

With the development of high performance materials for use in the aerospace and other industries there is a growing demand to measure temperature to a greater degree of accuracy and at higher temperatures.

During the last decade the need for temperature sensors to work accurately for longer under these high temperature conditions has increased to a point where the limitations of the type K thermocouple are being reached and in some cases exceeded.

The development of the type N (Nicrosil v Nisil) thermocouple and its application particularly for high temperature operation has allowed the use of base metal thermocouples to continue as the primary sensor for operations such as load, monitoring and thermal uniformity surveys.

It is widely understood that both the type K and type N thermocouple in operational conditions during extended and/or high temperature conditions have a limited accurate operational life. This has led to manufacturers and heat treaters having to look at using the less versatile and significantly more expensive Platinum/Rhodium (type R, S and B) noble metal thermocouples in temperature ranges above 1000 °C (1832 °F) for reliable and accurate measurements.

Limitations of Base Metal Thermocouples

The need for a more reliable and accurate base metal sensor was the driving force that started a long term investigation into understanding, in detail, why base metal thermocouples drift, by research scientists in the Department of Materials Science and Metallurgy at the University of Cambridge.

Significant research was conducted looking at the root causes of why particularly the type K thermocouple, shows accelerated drift under certain conditions, particularly at high temperatures. Substantial work has been conducted over the last 50 years into this field and most of the general mechanisms associated with drift were already known. The following mechanisms can be identified among the major causes of drift in base metal thermocouples:

1. Oxidation
2. Short range ordering
3. Depletion/change in composition
4. Other physical/chemical changes

Oxidation was, and continues to be, a major issue for bare wire thermocouples as it produces extensive change in composition as a result of the formation of oxide scales on the surface of the thermoelements.

The use of a protective outer sheath in the form of a mineral insulated thermocouple cable configuration has had a positive effect on reducing the contributions of oxidation. This has been clear for many years and the current mineral insulated cable construction design for base metal thermocouples, has been the major reason why the impact on drift of oxidation and other physical/chemical changes caused by the aggressive operating environment, have been significantly reduced under operational and high temperature conditions.

The development of the type N thermocouple combination in the 1960's had a positive effect on providing a temperature sensor with a reduced contribution of short range ordering, a condition that has a major contribution to drift in the lower temperature range.

The factor that had not been dealt with is the depletion/change in chemical combination of the conductors; in fact the mineral insulated construction can be considered as a factor which may contribute to a higher level of depletion/change that occurs during operational use.

Early studies conducted by researchers at the University of Cambridge have shown that base metal mineral insulated thermocouple conductors exposed at high temperatures experience increased levels of contamination from elements such as Mn and Cr. These studies have shown that the levels of these elements had penetrated deep into the thermocouple conductors after limited operational use.

The source of these and other chemical elements have been identified as being

i) The second thermocouple conductor
ii) The outer sheathing of the mineral insulated thermocouple cable.

Further research conducted at the University of Cambridge has confirmed the major source in terms of both volume and material that causes higher rates of drift is, in fact, the mineral insulated thermocouple outer sheathing.

As could be expected, the higher the temperature of operation the greater the rates of these changes. This varying amount of material changes down the thermocouple conductor's / cable length results in an increase of the heterogeneous nature of the base metal thermocouple conductors, therefore having a significant contribution to the observed rate of drift.

The mineral insulated thermocouple cable sheathing has been shown over the last 50 years to have had a significant effect on reducing the contributions of oxidation and other physical/chemical changes by protecting the thermocouple conductors from the external or operational environments. However, this same protective outer sheathing has now been confirmed, particularly at high temperature, as the major source of changes in composition of the thermocouple conductors and therefore source or cause of major thermocouple drift in mineral insulated constructions. The same sheathing that has allowed thermocouples to have a longer operational life, compared to bare wire sensors has become the largest barrier to increase further the operating temperature of the sensor and to fully exploit the potential of base metal thermocouples at highest temperatures.

The work conducted by researchers at Cambridge focused not only on the mechanisms and root causes associated with drift but also on methods to control the mechanisms and reduce their impact on the drift of sensors in order to increase the reliable operational life of a base metal thermocouple. This work has led to a new mineral insulated thermocouple cable design that addresses the issue of depletion/change in composition due to the contamination from the sheath to the thermoelements over significant time at high temperature.

The Solution

With the information that had been gathered by researchers it was considered that to reduce the drift in base metal mineral insulated thermocouples it would be necessary to reduce the transfer of elements from the cable outer sheathing across the mineral insulation (MgO) to the thermocouple conductors.

The typical sheathings currently used as mineral insulated cable outer sheathing, such as Inconel 600, 310, 316, 304 stainless steels, are able to work in demanding operating environments. However these same sheathing materials have also been shown to significantly contaminate the thermoelements during operation. A new sheath was needed to reduce the potential of contamination of the thermocouple conductors.

The New Design: The Dual Wall

With an innovative new design researchers from the University of Cambridge proposed to reduce the drift by putting a barrier, in the form of an additional inner sheath, between the normal outer sheath and base metal thermocouple conductors: this design will be called herein *dual wall* configuration and the resulting sensor dual wall thermocouples (Fig. 1).

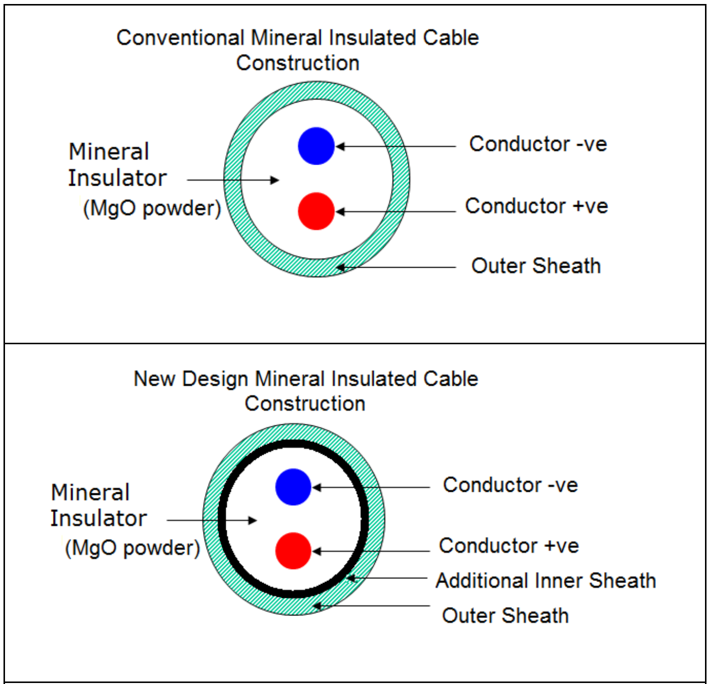

Figure 1

This led to work being required to find or develop a suitable inner sheathing that could be used in the manufacturing process of mineral insulated cable whilst also surviving the operational industrial thermal environments which these cables are used in. The new inner sheathing would have to meet the above requirement, whilst stopping or reducing the transfer of elements from the outer sheath that were creating the thermocouple conductor inhomogeneity and therefore the resultant thermocouple drift.

After significant investigation and testing a suitable alloy with the required properties was identified. Patents were filed and granted; manufacture of cables was undertaken, employing conventional mineral insulated thermocouple cable manufacturing techniques.

Laboratory Tests

A detailed program of both laboratory and industrial testing was then conducted to prove the concept.
The following are the latest results from a series of tests undertaken in the CCPI Europe Ltd UKAS accredited (Lab. No 0600) calibration laboratory.
The tests were conducted on both type K and type N Inconel 600 sheathed thermocouples, this being the construction of a large number of base metal thermocouples used in the aerospace heat treatment industry. All the thermocouples used in tests were manufactured using the same core batch material for both the conventional mineral insulated cable construction and the new design dual wall low drift construction.

Dual wall cables were manufactured for both type K and type N combinations at various diameters. All the tests were conducted in a calibration horizontal tube furnace with between 450 and 500 mm immersion depth. The operating atmosphere was air.

Thermal calibration of all the test sensors was conducted using standard type R calibrated reference standard thermocouples and a Fluke 8508A DMM as the measurement device.

All thermocouple readings were referenced to 0 °C (32 °F) and all measurements were referenced to the ITS 90 temperature scale.

A series of tests were conducted for both continuous high temperature and high temperature cycling conditions. The following gives details of the tests conducted and results showing the data obtained when comparing the new dual wall mineral insulated construction sensors directly against sensors manufactured using conventional mineral insulated construction cable.

Long Term High Temperature Cycling Test 3mm Nominal Diameter Cables
In this test thermocouples were subjected to a program of thermal cycling over the temperature range 450 to 1250 °C (842 to 2282 °F). The time and temperature profile used for a cycle is shown in Fig. 2. Each thermal cycle took just below 400 minutes to complete.

Two sets of test sensors of each design (conventional and dual wall) were manufactured for both constructions in type K and type N thermocouple combinations.
Due to the type K dual wall cable being a prototype it was only available as a 3.2 mm overall diameter Inconel 600 sheathed cable. The type K conventional construction used for tests was a 3.0 mm diameter Inconel 600 sheathed cable. For the type N thermocouple tests the conventional thermocouples were 3mm Inconel 600 constructions, the dual wall thermocouples were 3mm diameter with the outer sheath being Inconel 600 cable.
For the type K thermocouples calibration results of the test sensors were taken on the 1st cycle, 16th, 31st, 46th 61st, 76th and 91st cycles respectively.
Identical tests were conducted on the type N test sensors on the 1st cycle, 30th, 60th and 90th cycles.

These tests were conducted under laboratory conditions and the total combined test time for the nominal 90 cycles was just under 25 days. The test thermocouples were not subjected to any mechanical stress during the tests. Uncertainties of measurement for the calibrations were estimated to be between 1 and 1.4 °C (1.8 and 2.5 °F) with a coverage factor k=2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with international requirements.

Long Term High Temperature Cycling Results 3mm Nominal Diameter Cables
A summary chart of the results obtained for the type K test sensors is shown in Fig. 3.

Figure 3 shows the calibration results in the form of a correction chart for both the type K conventional sensors and the dual wall sensors. The chart shows the change in output for the respective test thermocouples between cycle 1 and cycle 91. The overall change in calibration values for the conventional sensor design was between
-10.6 and -17 °C (-19 and -30.6 °F) over the test duration. For the dual wall sensor design the overall change in calibration values was by between -0.5 and +2.9 °C (-1 and +5.3 °F).

A summary chart of the results obtained for the type N test sensors is shown in Fig. 4.

Figure 4 shows the calibration results in the form of a correction chart for both the type N conventional sensors and the dual wall sensors. The chart shows the change in output for the respective test thermocouples between cycle 1 and cycle 60. The tests were conducted over 90 cycles however both the test conventional thermocouples were noted to have failed between cycle 61 and 90. Hence comparative results are only stated up to cycle 60 of the test. The overall change in calibration values for the conventional sensor design after the 60th cycle was between -7.9 and -11.1 °C (-14.2 to -20.1 °F). While for the dual wall type N sensor design the overall change in calibration at the 60th cycle values was between -2.1 and -2.7 °C (-3.7 to -4.9 °F). It should be noted for the 90th cycle for the dual wall design this had stabilised between -1.9 and -3.3 °C (-3.4 and -6 °F).

Summary of Dual Wall Cable Design Long Term High Temperature Cycling Results 3mm Nominal Diameter

The type K dual wall new design cable demonstrated an average 89.6% reduction in drift over all tests at all test temperatures after 91 cycles, with a maximum shift in calibration values between the 1st and 91st cycle being 2.9 °C (5.2 °F) against a maximum 17 °C (30.6 °F) value shown by the conventional mineral insulated cable design.

The type N dual wall new design demonstrated an average 74.8% reduction in drift over all tests at all test temperature after 60 cycles, (note that no comparison could be made at 90 cycles as the conventional mineral insulated cables were open circuit after 60 cycles), with a maximum shift in calibration values between the 1st and 90th cycle being 3.3 °C (6 °F).

Short Term High Temperature Cycling Test 1.5mm Diameter Cables

In this test thermocouples were once again subjected to a program of thermal cycling over the temperature range 450 to 1250 °C (842 to 2282 °F). The time and temperature profile used for a cycle is shown in Fig. 2 Each thermal cycle took just below 400 minutes to complete.

One of each test sensors design was manufactured for both constructions (conventional and dual wall) in type K and type N mineral insulated thermocouples.

The type K dual wall thermocouple was a 1.5 mm diameter Inconel 600 outer sheathed cable. The type K conventional construction used for tests was also a 1.5 mm diameter Inconel 600 sheathed cable. For the type N thermocouple tests the conventional thermocouple was a 1.5 mm diameter Inconel 600 sheathed cable construction, while the dual wall thermocouple was a 1.5 mm diameter Inconel 600 outer sheathed cable.

For both the type K and type N thermocouples calibration results of the test sensors were taken on the 1st cycle, 10th and 20th cycles, respectively.

These tests were conducted under laboratory conditions and the total combined test time was just under 5.5 days. The test thermocouples were not subjected to any mechanical stress during the tests. Uncertainties of measurement for the calibrations were estimated to be between 1 and 1.4 °C (1.8 and 2.5 °F), with a coverage factor k=2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with international requirements.

Short Term High Temperature Cycling Results 1.5mm Diameter Cables

A summary chart of the results obtained for the type K test sensors is shown in Fig. 5.

Figure 5 shows the calibration results in the form of a correction chart for both the type K conventional 1.5mm diameter sensors and the 1.5mm diameter type K dual wall sensors. The chart shows the change in output for the respective test thermocouples between cycle 1 and cycle 20. The overall change in calibration values for the 1.5mm diameter conventional sensor design was between -8 and -10.4 °C (-14.4 and -18.7 °F), over the 20 cycle test duration. While for the 1.5mm diameter dual wall sensor design the overall change in calibration values was between -2.7 and +1.8 °C (-4.9 and +3.2 °F).

A summary chart of the results obtained for the type N test sensors is shown in Fig. 6.

Figure 6 shows the calibration results in the form of a correction chart for both the type N conventional 1.5mm diameter sensors and the type N 1.5mm diameter dual wall sensors, the chart shows the change in output for the respective test thermocouples between cycle 1 and cycle 20. The overall change in calibration values for the 1.5mm diameter conventional sensor design was between -7.5 and -8.7 °C (-13.5 and -15.7 °F) over the 20 cycle test duration, while for the 1.5mm diameter dual wall sensor design the overall change in calibration values was between +1.2 and +2 °C (+2.2 and +3.6 °F).

Summary of Dual Wall Cable Design Short Term High Temperature Cycling Results 1.5 Mm Diameter

The type K 1.5mm dual wall design demonstrated an average 78.7% reduction in drift over all tests at all test temperatures after 20 cycles, with a maximum shift in calibration values between the 1st and 20th cycle being 2.7 °C (4.9 °F) against a

maximum 10.3 °C (18.5 °F) value shown by the conventional mineral insulated cable design.
The type N dual wall 1.5 mm design demonstrated an average 80.3% reduction in drift over all tests at all test temperature after 20 cycles, with a maximum shift in calibration values between the 1st and 20th cycle being 2 °C (3.6 °F) against a maximum 8.7 °C (15.7 °F) value, shown by the conventional mineral insulated cable design.

High Temperature Continuous Operational Test at 1320 °C (2408 °F).
In this test thermocouples were not subjected to thermal cycling conditions but held at a constant high temperature and monitored at regular intervals. The high temperature point selected was 1320 °C (2408 °F). This temperature is well above the maximum recommended temperature for either type K or type N.

One of each test sensors design was manufactured for both constructions in type K and type N thermocouples

The type K dual wall cable was a 3.2mm diameter Inconel 600 outer sheathed cable, the type K conventional construction used for tests was a 3 mm diameter Inconel 600 sheathed cable. For the type N thermocouple tests both the dual wall and conventional cables used were also 3mm Inconel 600 sheathed constructions.

For both the type K and type N thermocouples calibration results of the test sensors were taken at regular intervals over the duration of the test.

These tests were conducted under laboratory conditions and the total combined test time was 52 hours. The test thermocouples were not subjected to any mechanical stress during the tests. Uncertainties of measurement for the calibrations were estimated to be between 1.5 and 1.8 °C (2.7 and 3.2 °F) with a coverage factor k=2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with international requirements.

High Temperature Continuous Operation of 1320 °C °C (2408 °F) Results
A summary chart of the results obtained for the type K test sensors is shown in Fig. 7.

Figure 7 shows the calibration results in the form of a correction chart for both the type K conventional 3mm diameter sensors and the 3.2mm diameter type K dual wall sensors. The chart shows the measured output as a correction value for the respective test thermocouples over time during the 52 hour test period. The overall change in calibration values for the 3mm diameter conventional sensor design was from a start correction value +2.9 °C to a final correction value of +14.5 °C (+5.2 to +26.1 °F), over the 52 hour test duration. Giving a total change value of 11.59 °C (20.9 °F). While for the 3.2 mm diameter dual wall sensor design was from a start correction value +2.3 °C to a final correction value of +5.2 °C (+4.1 to +9.4 °F) over the 52 hour test duration, giving a total change value of 2.95 °C (5.3 °F).

A summary chart of the results obtained for the type N test sensors is shown in Fig. 8.

Figure 8 shows the calibration results in the form of a correction chart for both the type N conventional 3mm diameter sensors and the 3mm diameter type N dual wall sensors, The chart shows the measured output as a correction value for the respective test thermocouples over time during the 52 hour test period. The overall change in calibration values for the 3mm diameter conventional sensor design was from a start correction value -1.44 °C to a final correction value of +4.2 °C (-2.6 to +7.6 °F) over the 52 hour test duration, giving a total change value of 5.65 °C (10.2 °F). While for the 3mm diameter dual wall sensor design was from a start correction value -1.87 °C to a final correction value of -0.34 °C (-3.4 to -0.6 °F) over the 52 hour test duration, giving a total change value of 1.53 °C (2.8 °F)

Summary of Dual Wall Cable Design High Temperature Continuous Results at 1320 °C (2408 °F).
The type K 3.2mm dual wall design demonstrated an average 74.6% reduction in drift over the test period, with a maximum shift in calibration values after 52 hours at 1320 °C (2408 °F) of 2.95 °C (5.3 °F) against a maximum 11.59 °C (20.9 °F) value shown by the conventional mineral insulated cable design.

The type N dual wall 3 mm design demonstrated a 72.9% reduction in drift over the test period, with a maximum shift in calibration values after 52 hours at 1320 °C (2408 °F) of 1.53 °C (2.8 °F) against a maximum 5.65 °C (10.2 °F) value shown by the conventional mineral insulated cable design.

Additional Information on Test Cycle
The temperature cycle time and temperatures for these cycling tests were selected to give as close a simulation as possible to operational conditions when thermocouples are used for temperature uniformity surveys to meet aerospace heat treatment specifications such as AMS 2750 rev E, BAC 5621 rev K and RPS 953 issue 21.

Conclusion

The test results showed that the new dual wall design mineral insulated cables not only perform with a significant reduction in drift in the higher temperature (> 1000 °C [>1830 °F]) range in the larger diameters (3mm) but also this reduction in drift and therefore increase in operational life continues to be displayed in the smaller diameters (1.5mm), which are often used but not recommended for use, in this high temperature range. The tests show the performance of the new dual wall low drift mineral insulated cables whether in type K or type N, 3mm or 1.5mm diameters gives between a 75 to 89% reduction in drift characteristics under high temperature cycling conditions. In addition during continuous high temperature conditions the dual wall cable also shows significantly improved reduced drift performance, this time showing between a 73% and 75% reduction. The overall effect to this reduction in drift is an increase in reliable life performance under high temperature either cycling or continuous operations. The new dual wall cable construction enables base metal thermocouple performance to stay within the IEC 60584 -1: 2013 class 1 and ASTM E230 special tolerances for a longer more useful time.

Type K Under High Temperature Conditions

Since its development in the 1960's the type N thermocouple combination has always been the recommended base metal thermocouple for high temperature operations. In fact, as indicated, that is why the type N combination was originally developed. With the development of this new dual wall mineral insulated technology the performance of the type K combination has been raised to match, or, under certain criteria better the high temperature capabilities of the type N. This may result into the type K dual wall thermocouple becoming the recommended base metal sensor for operation between 1320 and 1350 °C (2408 and 2462 °C), where the type N thermocouple may not be used due to the incipient melting of the Nisil (-ve) thermoelement: further tests are currently planned to thoroughly assess the performance of the dual wall type K thermocouples in this extremely demanding temperature range.

Independent Review

Interest in the new dual wall cable design has been very high and its application for numerous high temperature, high duration, high accuracy uses in industry are currently being investigated.
Several industrial tests using the dual wall thermocouple cable designs in heat treatment applications have been planned and are currently on-going as part of EMPRESS. In addition metrology institutes have shown interest in running independent test campaigns as part of future joint research projects.

The Next Step in R&D

The potential of the dual wall thermocouple configuration has only been partially explored so far and further development is needed to entirely determine its benefits.

An optimisation of the inner and outer wall thicknesses can lead to tailor to specific applications the performance of the dual wall thermocouples, in terms of both drift and life. The flexible design provided by the dual wall thermocouples and the optimisation process also offer the opportunity to increase the thermoelements diameter, initially used for the first prototypes of the dual wall thermocouples: this potentially will have the effect of reducing drift rates further.

Standardisation

The current data and results on dual wall thermocouples will be brought to the attention of standardisation committees: standardisation will allow a large industrial community to profit from the improved performance provided by dual wall construction thermocouples.

Appendix

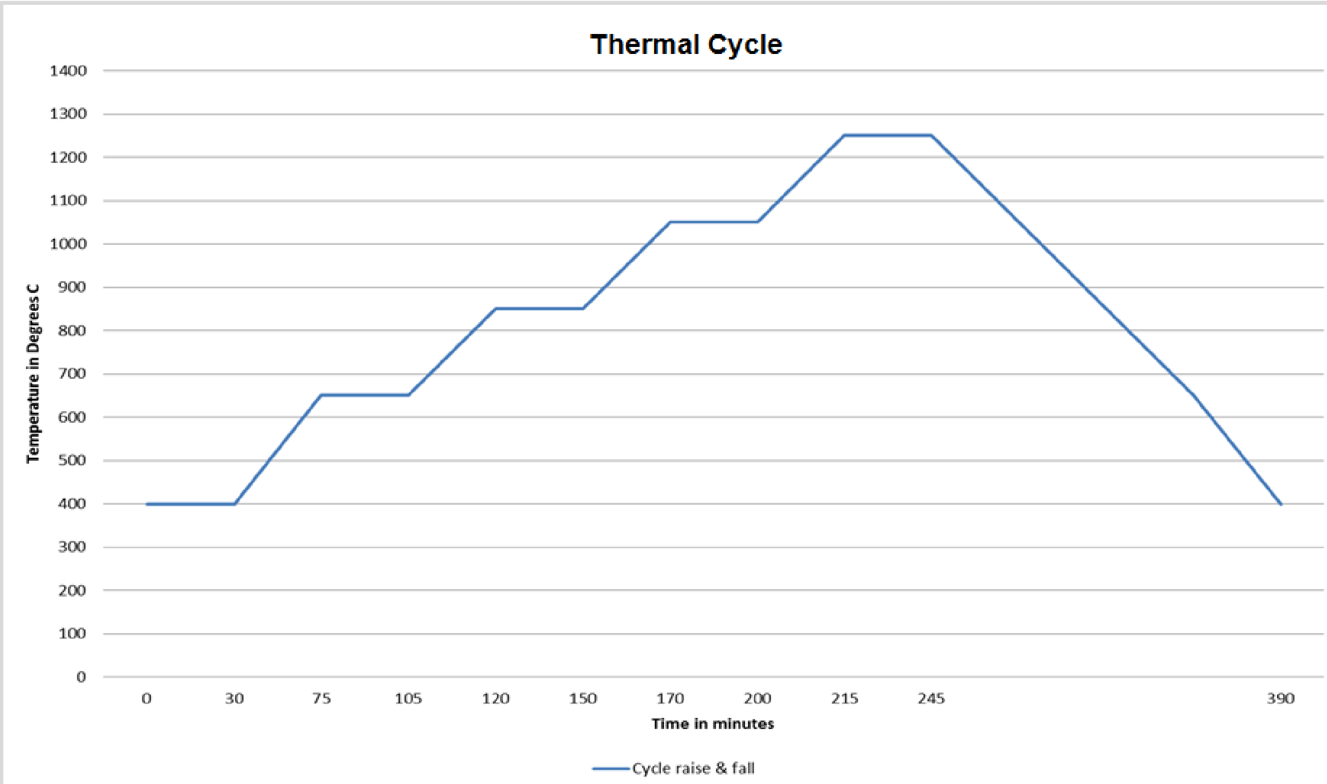

Figure 2

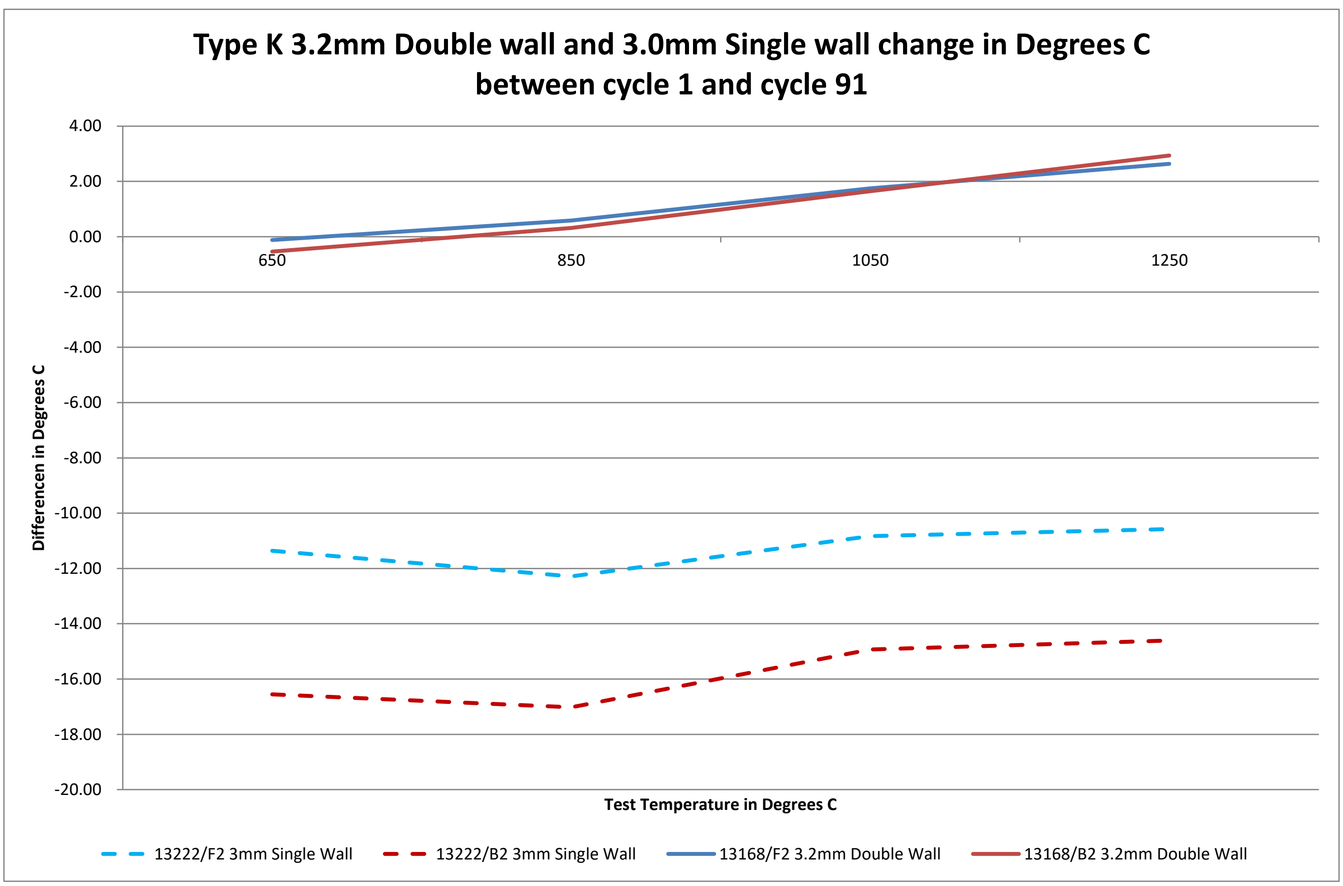

Figure 3

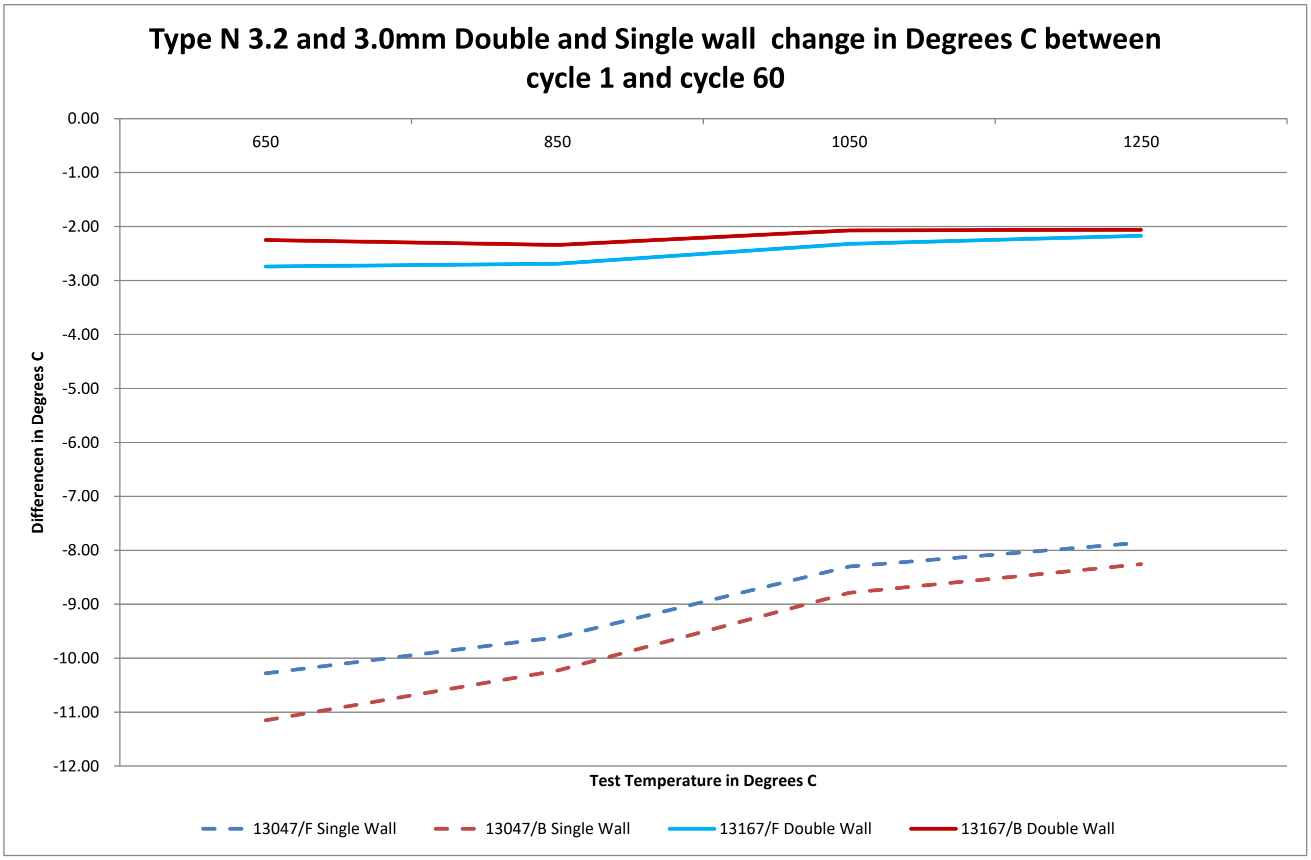

Figure 4

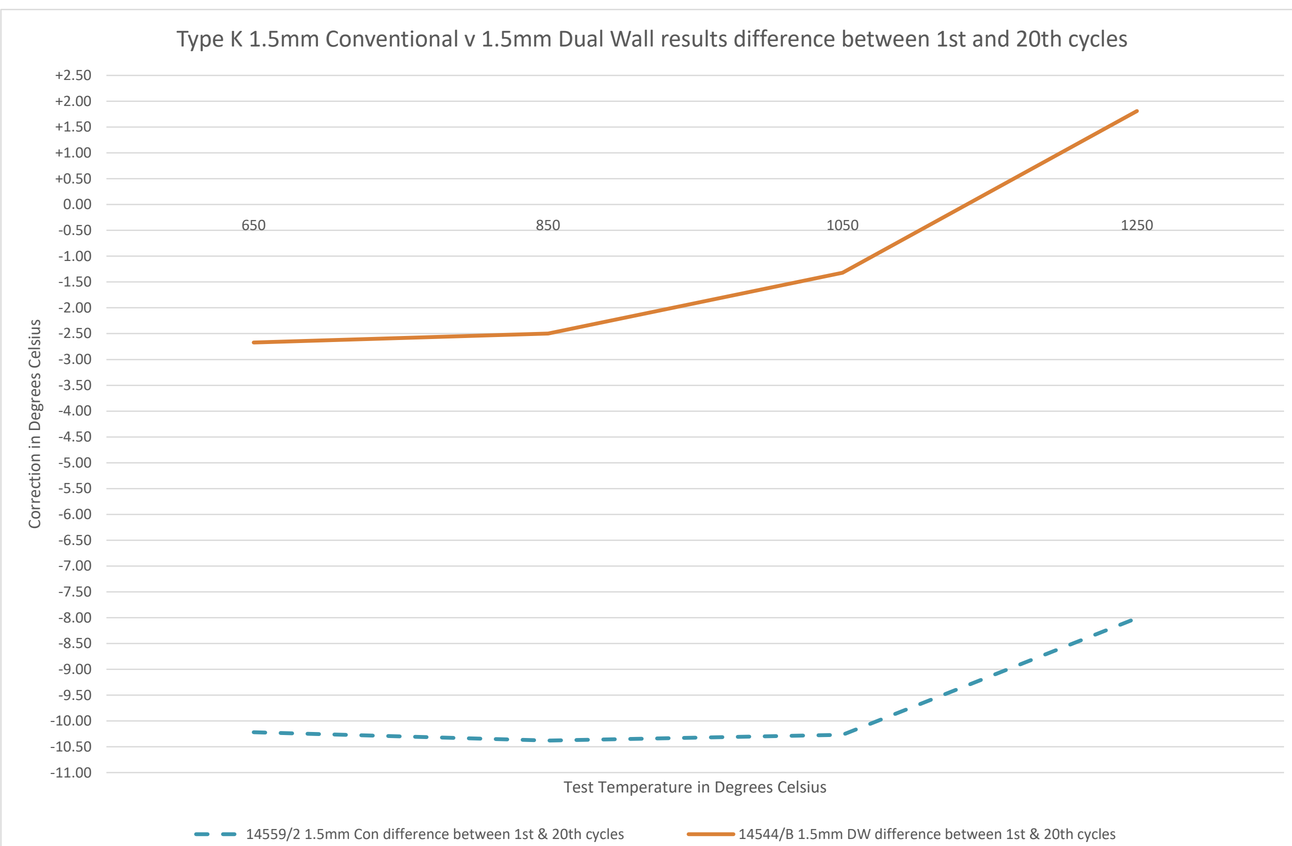

Figure 5

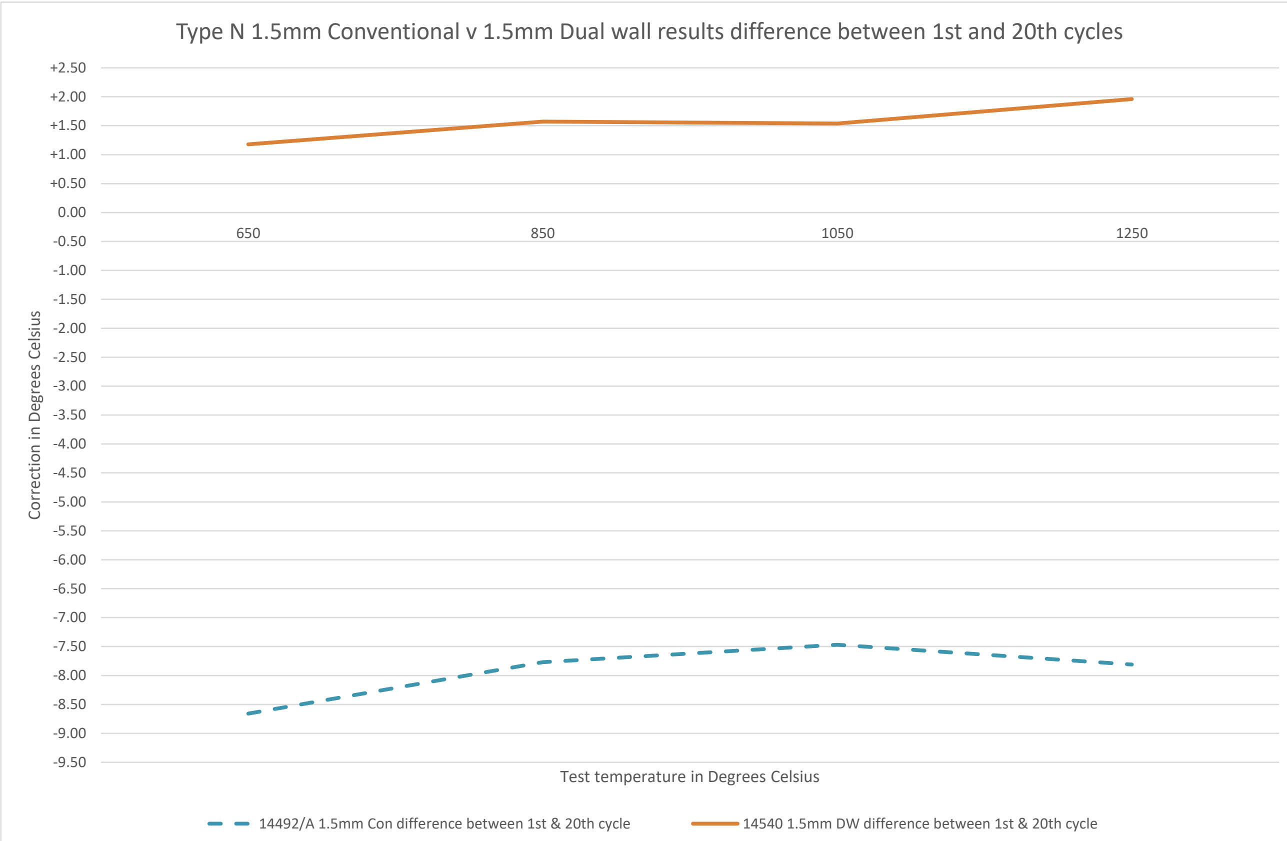

Figure 6

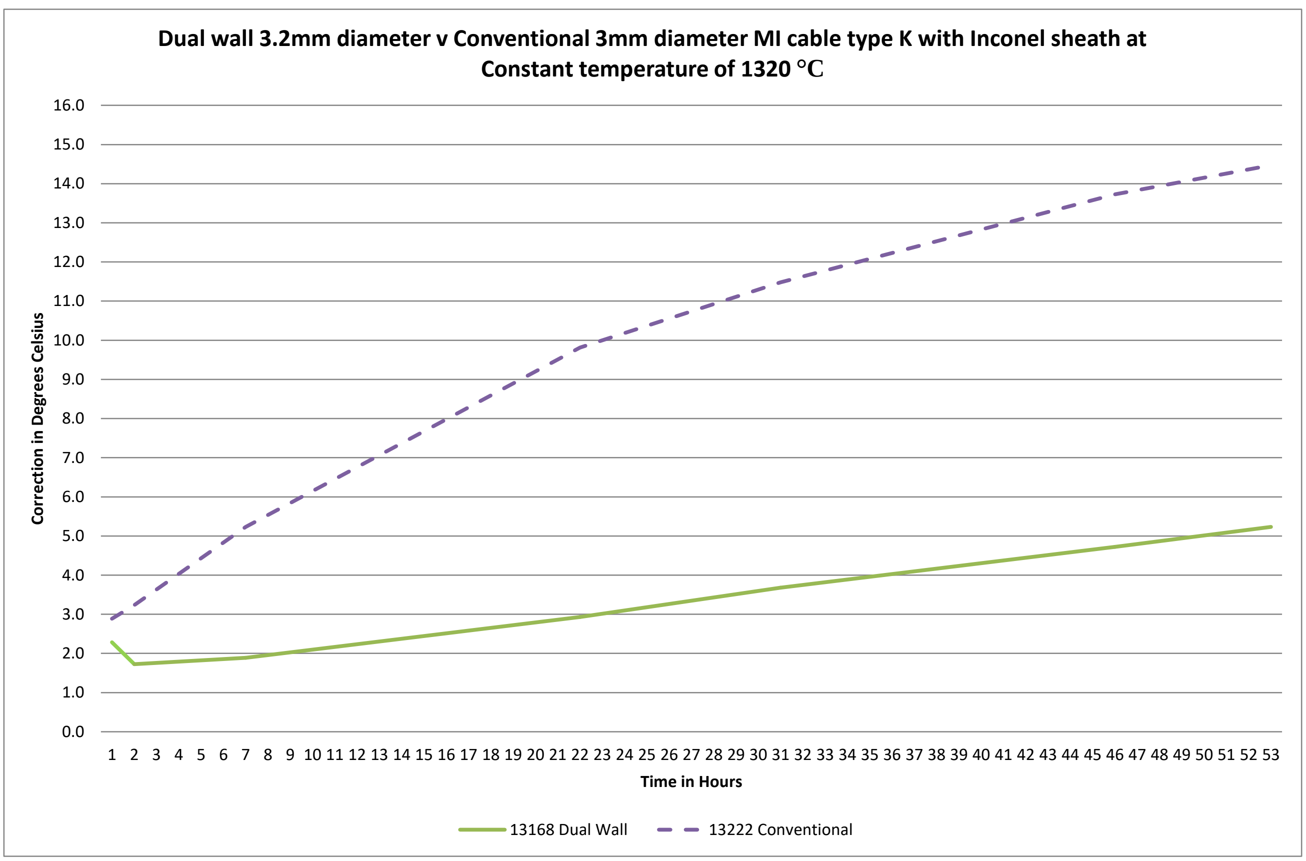

Figure 7

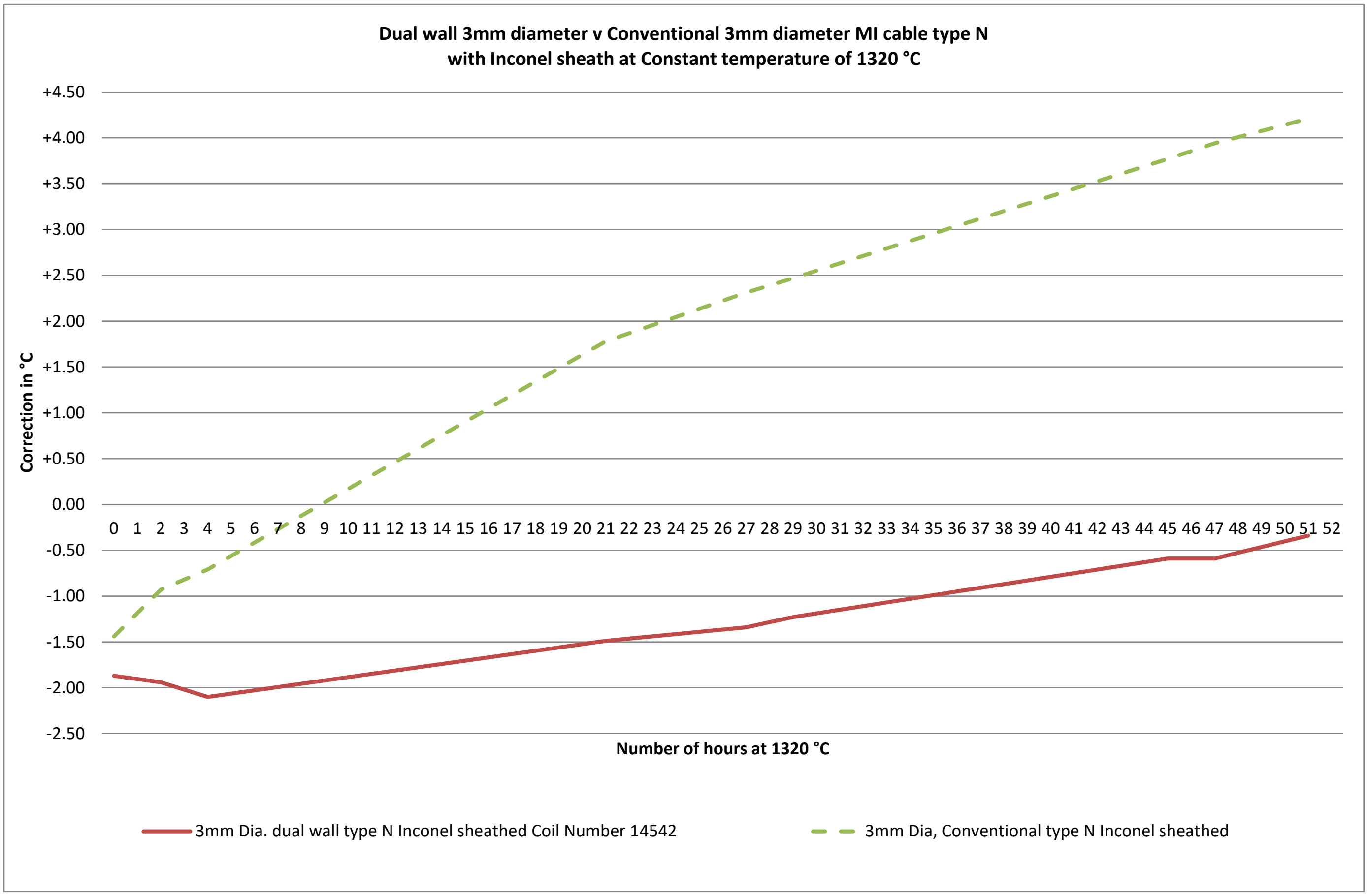
Dual wall 3mm diameter v Conventional 3mm diameter MI cable type N
with Inconel sheath at Constant temperature of 1320 °C
Correction in °C
+4.50
+4.00
+3.50
+3.00
+2.50
+2.00
+1.50
+1.00
+0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
Number of hours at 1320 °C
3mm Dia. dual wall type N Inconel sheathed Coil Number 14542
3mm Dia, Conventional type N Inconel sheathed

Figure 8

-End-