# Development of a specialised calibration and infra-red emissivity correction to enable the temperature monitoring of intermediate level nuclear waste using thermal imaging

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*Abstract*— **The temperature measurement of intermediate level nuclear waste containers is vital to monitor thermal stability and track temperature trends over time. The use of thermal imaging for this monitoring has numerous advantages compared to using a single spot radiation thermometer, and Sellafield wish to employ this approach for their '3 m$^3$ box' intermediate level waste containers. In order to achieve this objective with confidence a custom temperature calibration is required for low uncertainty temperature measurement. Another key consideration for practical non-contact temperature measurement is the emissivity of the surface being measured at the relevant infra-red wavelengths, as such the emissivity of the Sellafield 3 m$^3$ box materials was measured and then corrected for. The implementation of a calibrated instrument and emissivity correction were validated using temperature controlled, 1:10 scale model 3 m$^3$ box containers within a climatic chamber. The surface temperature of the scale containers was determined to an uncertainty of ± 6.5 °C ($k$ = 2.1) for the container walls, ± 3.5 °C ($k$ = 2.1) for the container lid and ± 1.5 °C ($k$ = 2.1) for the container vents. The measurement techniques used to determine the temperature of the 1:10 scale 3 m$^3$ box containers were therefore successful and there is a clear development path to monitoring the containers in storage using thermal imaging.**

*Keywords* — **Nuclear decommissioning waste radiation temperature thermal imaging monitoring safety stability**

## I. INTRODUCTION

A significant portion of radioactive material stored at the Sellafield site in Cumbria, UK is classified as intermediate level waste. This waste was traditionally stored at the base of open pools, but it is now being moved to medium term storage containers.

The primary container to be used for this storage is the '3 m$^3$ box'. The container system consists of a vented inner skip holding the immersed nuclear waste and an outer 3 m$^3$ box with lid vents to allow for cooling and gas release. An exploded view diagram of this box can be seen in Fig. 1.

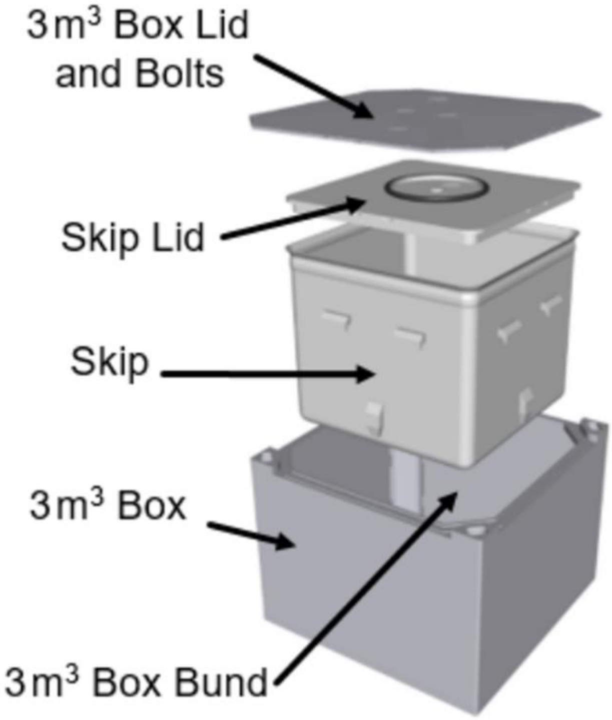

Fig. 1. Diagram showing structure of 3 m$^3$ box internal structure with waste skip and external box [1].

The activity level of intermediate level waste mandates that a method of temperature monitoring is used to track the thermal evolution of the 3 m$^3$ waste packages over time. The use of thermal imaging for this monitoring enables the detection of box non-uniformity, hot spots, and other visual artefacts. However, for confidence in the measured temperature the thermal imager must be calibrated to traceable national standards and in a way that accounts for the anticipated environmental temperature range within the store which will alter the device's operating temperature, impacting measurements.

Similarly, the surface emissivity of the 3 m$^3$ box materials at the wavelength, temperature, and angle captured by the thermal imager must be measured, this enables the correction of measurements when dealing with the apparent total infra-red radiation from the box surfaces as captured by a thermal imager. This is because the reflected radiation from the measurement surface will represent the temperature of the environment, because of this the proportion of infra-red radiation from each source, emitted or reflected, must be known. A robust knowledge of the surface emissivity of major 3 $m^3$ box materials is therefore a critical factor in the reliable measurement of the container's surface temperature.

A custom temperature calibration, box material emissivity measurements and emissivity correction were all addressed within this activity to enable future 3 $m^3$ box temperature measurement and monitoring.

## II. EXPERIMENTS & METHODS

### A. *Thermal imager calibration*

A low cost, off the shelf, low size weight and power thermal imager was used for this research. The same model of thermal imaging core is envisaged to be used by Sellafield for the final application as their low cost makes them easily replaceable when they succumb to radiation damage. However, before any thermal imager measurements can be gathered a custom calibration needed to be performed.

The thermal imager was calibrated within a climatic chamber across an environmental temperature range of 7.5 °C to 27.5 °C, with this representing the nominal temperature range within the operational 3 $m^3$ box store. Humidity was not controlled as this improved the temperature stability within the chamber. The temperature calibration range was from 7.5 °C to 37.5 °C, with this range representing the expected apparent temperature of the 3 $m^3$ boxes. This temperature range was determined using earlier thermal imager measurements of a 3 $m^3$ box with an artificial internal heat source.

The thermal imager was calibrated using a high emissivity cavity blackbody positioned outside the climatic chamber and viewed through a porthole. An example calibration image can be seen below in Fig. 2, the region of interest used to gather raw 16-bit digital value data is shown in red.

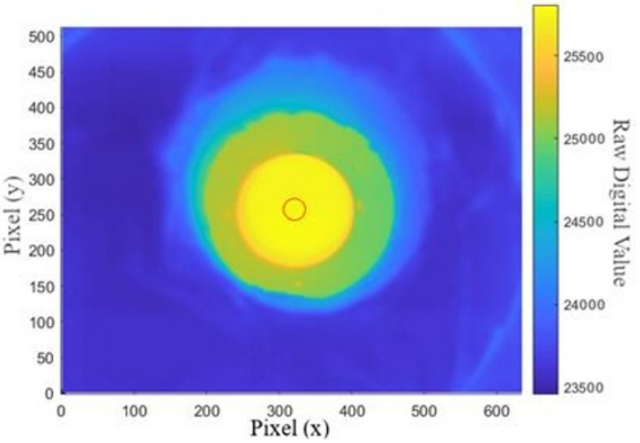

Fig. 2. Example calibration thermal imager showing reference blackbody.

### B. *Emissivity measurements*

Samples of the vent metallic mesh, wall steel, and lid steel from 3 $m^3$ boxes were provided to the National Physical Laboratory (NPL) by Sellafield Ltd., these were cut to size and dispatched to Physikalisch-Technische Bundesanstalt (PTB), the National Metrological Institute of Germany to complete the spectral directional emissivity measurements of the samples using their infra-red spectrometer [2]. The dispatched vent material is shown in Fig. 3.

PTB completed emissivity measurements at 15 °C and 60 °C at a wavelength range of 5 µm to 14 µm and at seven angles of observation ranging from 10° to 70° from the normal to the sample surface. These results were delivered to NPL in full for use in the measurement correction for non-perfect emissivity.

Fig. 3. 90 mm discs of ~ 1 m thickness vent material sent to PTB for surface emissivity measurements.

### C. *Scale box measurements*

A 1:10 scale storage environment was set up inside the NPL thermal imaging team's climatic chamber. The temperature of the environment was controllable across the required temperature range, with a temperature stability of nominally ± 0.1 °C.

Plywood panels, fitted within the chamber, were given a ~1 mm coating of Secrete to mimic the concrete surfaces of the storage facility walls, ceiling and floor, this provided a more realistic background environment with estimated surface emissivity of approximately 0.95. These panels were cut to size and attached to the climatic chamber walls, ceiling, and floor, this ensured that the first material reflected in the lid, vent, and outer wall of each scale 3 $m^3$ box was a concrete analogue, as would be observed in the operating store. The surfaces of the 1:10 scale boxes were constructed with steels that matched the composition and finish of the 3 $m^3$ box wall and lid, with actual vent material used for the four vents on each lid. The scale boxes and false concrete walls of the climatic chamber are shown in Fig. 4.

Each 1:10 scale box was fitted with a 12-Watt heater which was used to increase the internal temperature to generate an external surface temperature matching that of a full-size container.

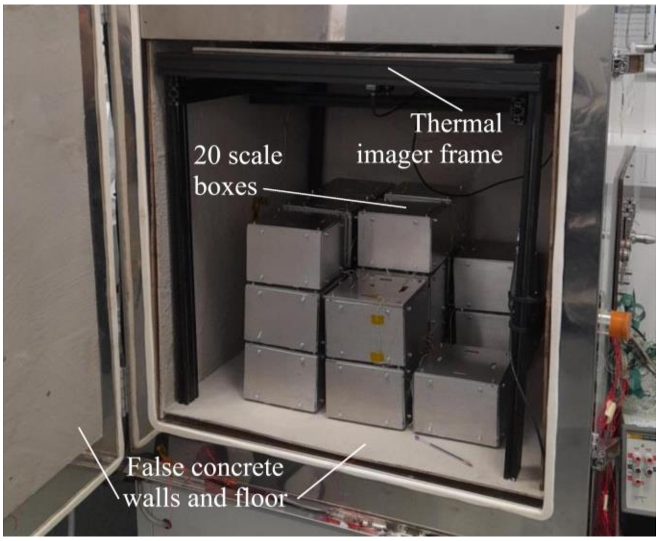

Fig. 4. External view of climatic chamber with false concrete walls and modified 1:10 scale boxes in place.

Four of the scale boxes were chosen to be measurement boxes, these were instrumented with surface mounted thermocouples to provide temperature references and their internal heaters were wired on a separate loop to be able to simulate elevated internal temperatures. These four boxes were given the arbitrary labels of "Red", "Blue", "Orange" and "Purple". The position of these boxes is shown below in Fig. 5. Thermal images were captured in 9 different positions above the four measurement boxes.

A total of 28 contact temperature sensors – measuring scale box surface temperature, chamber wall surface temperature and air temperature – were placed throughout the climatic chamber and boxes, in addition to a calibrated humidity sensor and chamber control sensor.

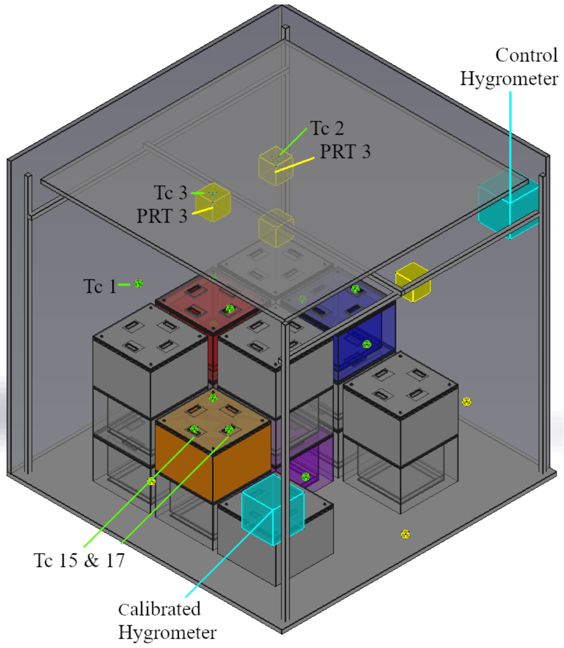

Fig. 5. 3D Diagram of climatic chamber measurement setup. The four instrumented and thermally imaged boxes are shown (Red, Orange, Blue & Purple) in addition to select thermocouple (Tc), Platinum Resistance Thermometer (PRT) and hygrometer locations.

For the measurement campaign nine different conditions were simulated using three environment temperatures (16 °C, 20 °C and 25 °C) and three box simulated temperatures. The non-measurement boxes remained at their expected normal temperature throughout. The measurement box external surfaces were thermally imaged at the expected surface temperature and two elevated surface temperatures of 2.5 °C and 5 °C above normal, with this simulating the expected change that would be seen in a full-scale container with an internal temperature 5 °C and 10 °C above normal, with the normal temperature assumed to be 45 °C

### D. *Emissivity correction*

A correction for non-perfect emissivity was applied to the thermal imager measured temperature using a simplified representation of the total infra-red radiation – emitted and reflected – that the thermal imager captured, with this total producing the apparent 3 m$^3$ box temperature. Under this simplification the reflected component was taken to have the temperature of the chamber walls, ceiling, or floor. In practice this meant the temperature of the closest chamber surface thermocouple to where the angle of incidence met the surface. For simplicity the chamber surfaces were assumed to have a perfect emissivity (i.e.,1.0), as opposed to the actual value of around 0.95. Using the apparent temperature and the approximated reflected component the emitted component could then be calculated.

The data used for the emissivity correction is shown in Fig. 6. The emissivity of the three main box materials and responsivity of the thermal imager are all shown with respect to wavelength.

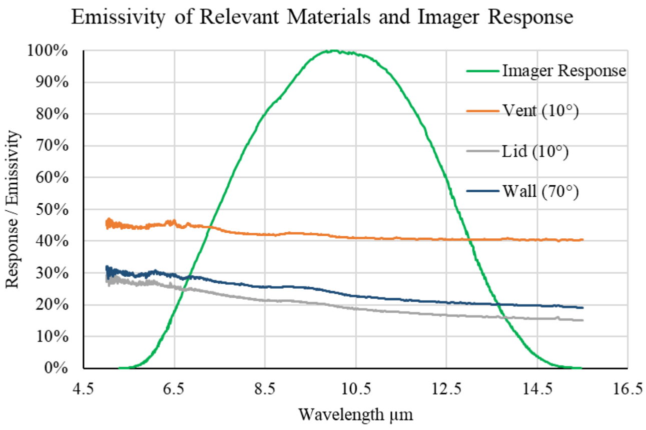

Fig. 6. Relative response of thermal imager and 3 m$^3$ box material emissivity results at relevant wavelengths

## III. RESULTS & DISCUSSION

### A. *Thermal imager calibration*

The thermal imager was calibrated with an uncertainty of ± 0.91 °C ($k$ = 2.1, 95% confidence interval). This represents the measurement uncertainty of the instrument measuring apparent surface temperature. The main contributors to this uncertainty were the non-uniformity of the thermal imager array and the repeatability of measurements when viewing a stable source, the results of the calibration validation are shown in Table 1.

This validation of the calibration was performed by measuring the temperature of the reference blackbody using the thermal imager at a non-calibration blackbody temperature and environmental temperature and then calculating the temperature differential between the two.

TABLE 1
VALIDATION OF THERMAL IMAGER CALIBRATION

| Thermal imager array temperature (°C) | Reference blackbody temperature (°C) | Thermal imager measured temperature (°C) | Temperature differential (°C) |
|---|---|---|---|
| 15.4 | 7.41 | 7.43 | -0.02 |
| 28.0 | 30.00 | 30.11 | -0.11 |
| 17.8 | 35.00 | 35.07 | -0.06 |
| 33.1 | 35.00 | 34.88 | 0.12 |
| 17.9 | 9.98 | 10.19 | -0.21 |
| 33.0 | 9.98 | 10.02 | -0.04 |
| 22.9 | 20.00 | 19.99 | 0.02 |

### *B. Emissivity measurements*

All three sample materials were successfully measured in terms of their directional spectral emissivity at two sample temperatures. The uncertainty of these measurements was a maximum of ± 0.03 ($k = 1$), this is an excellent measurement uncertainty for material infra-red emissivity, but the material emissivity uncertainty remained one of the main contributors to the emissivity correction's overall uncertainty.

### *C. Scale box measurements*

The nine environmental conditions and nine thermal imager measurement positions resulted in a data set of 81 thermal imager measurement series. Twelve measurement images were captured at each measurement position within a 30 second period. These were imported into MATLAB and the image series was averaged into a single frame. The data was captured in the same 16-bit format used for calibration and the calibration was used to convert the averaged frame digital values to temperature values.

Two examples of the thermal images captured are shown in Fig. 7, the higher apparent temperature of the four vents is clearly visible in addition to the reflection of the thermal imager itself in the box lids. An area of high emissivity tape was used on half of some vents to provide a thermal imager measured value closer to the true surface temperature.

The region of interests used to measure the vent temperature and the high emissivity surface temperature are shown as black squares. The regions used to measure the lid surface temperature are shown as red circles and these were positioned either side of the surface mounted reference thermocouples.

A visual reference for these features can be seen in Fig. 8.

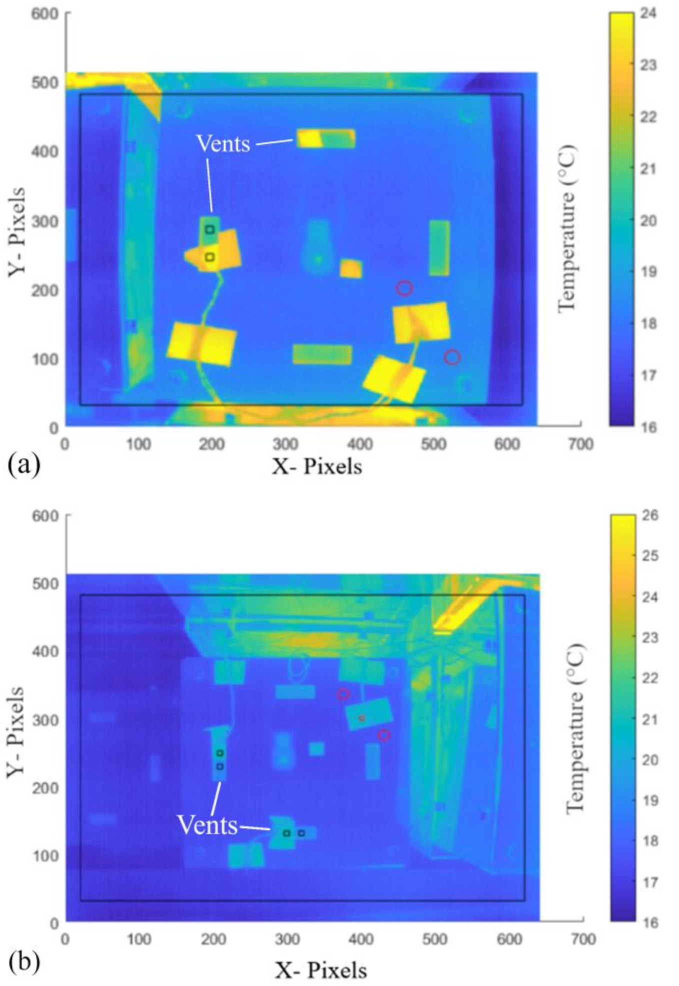

Fig. 7. (a) Thermal image of 'Red' box lid. (b) Thermal imager of 'Orange' box lid. Both images were taken from an overhead position with scale showing apparent temperature.

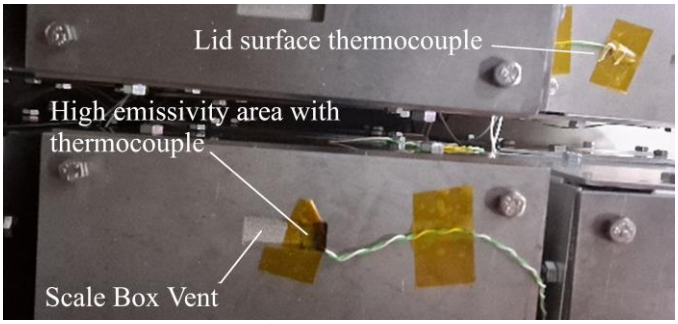

Fig. 8. Visual reference of 3 m$^3$ box lid & vent, surface mounted thermocouple and high emissivity area are highlighted.

The (calibration corrected, but not emissivity corrected) apparent temperature results of the measurement boxes showed that an elevated box surface temperature was detectable using a thermal imager at all environmental temperatures. The observed apparent temperature change was less than was measured using the reference thermocouples, but this was to be expected due to the non-perfect emissivity of the box materials. An example of these apparent temperature results is shown in Fig. 9.

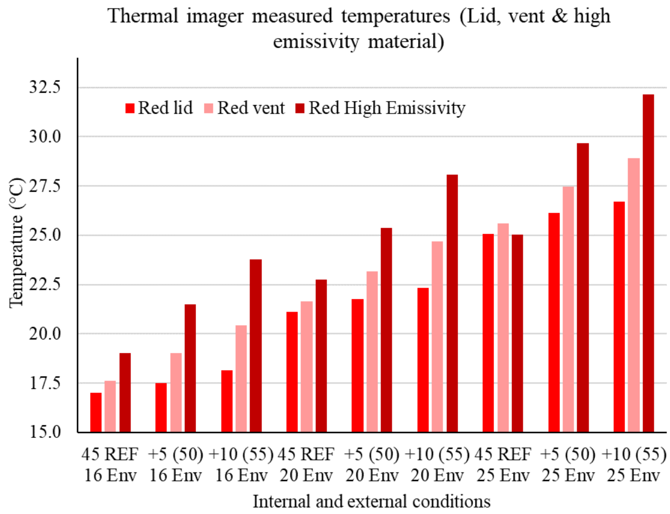

Fig. 9. Apparent temperatures of box upper surfaces as measured by thermal imager. X-axis labels show the modelled box internal conditions in top row, 45°C internal reference temperature “45 REF”, 5 °C above normal “+5(50)” & 10 °C above normal “+10 (55)”. The chamber environmental conditions are shown in the second row, 16 °C Environment “16 Env”, 20 °C Environment “20 Env” and 25 °C Environment “25 Env”.

### D. *Emissivity correction*

Example results showing the impact of emissivity correction for the ‘Red’ box vent and ‘Blue’ box lid are shown in Fig. 10 & 11 respectively. It can be clearly seen that the corrected temperature value is much closer to that measured by the reference thermocouple. Changes in surface temperature are also more detectable, with a larger temperature differential measured for the elevated condition versus the normal condition.

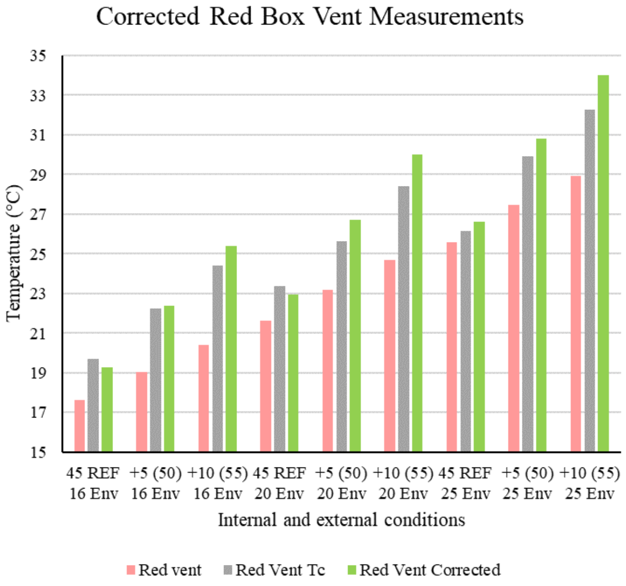

Fig. 10. Comparison of apparent surface temperature measured for vent with reference thermocouple value and emissivity corrected value

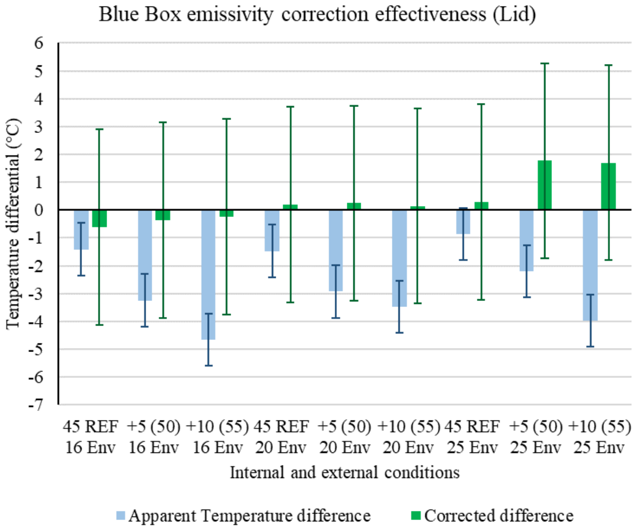

Fig. 11. Comparison of apparent temperature with surface temperature calculated using emissivity correction, the reference thermocouple temperature is taken as the true surface temperature, represented as zero on the y-axis

The average remaining measurement differential between the contact temperature measurement and the thermal imager measured temperature was 0.81 °C, down from 2.8 °C for the uncorrected, apparent box temperatures. The results across the different measurement boxes are shown in Table 2. The emissivity correction reduced the differential between the measured temperature and the reference thermocouple temperature for all measurement boxes and their surfaces

TABLE 2
RESULTS OF EMISSIVITY CORRECTION

| Measurement and reference thermocouple location | Non-emissivity corrected differential (°C) | Emissivity corrected differential (°C) |
|---|---|---|
| Red lid | 3.7 | 0.8 |
| Red vent | 2.6 | 0.9 |
| Red outer Wall | 5.0 | 0.7 |
| Blue Lid | 2.7 | 0.6 |
| Blue Vent | 3.5 | 0.8 |
| Orange lid | 2.4 | 1.3 |
| Orange Vent | 2.2 | 0.4 |
| Purple outer Wall | 2.7 | 0.9 |
| Red box inner wall | 1.7 | 1.1 |
| Orange box inner wall | 2.7 | 0.8 |
| Blue box outer wall | 1.7 | 0.6 |
| **Average** | **2.8** | **0.8** |

The uncertainty of the emissivity correction was also calculated, and this equated to a total application measurement uncertainty of ± 3.5 °C ($k$ = 2.1) for the box lid, ± 1.55 °C ($k$ = 2.1) for the box vents and ± 6.5 °C ($k$ = 2.1) for the box walls. Key uncertainty contributors were the material emissivity measurement and the uncertainty in determining the background temperature that generated the reflected infra-red component.

## IV. CONCLUSIONS

The temperature measurement of intermediate level nuclear waste containers is vital for condition monitoring and inspection. The use of thermal imaging, employing a bespoke calibration and surface emissivity correction approach have been successfully validated using temperature controlled, 1:10 scale model waste storage containers within a controlled mimic environment (climatic chamber). The surface temperature of the scale containers was determined to an uncertainty of ± 6.5 °C ($k = 2.1$) for the container walls, ± 3.5 °C ($k = 2.1$) for the container lid and ± 1.5 °C ($k = 2.1$) for the container vents.

The results show that thermal imaging can successfully identify scale boxes that have an elevated surface temperature under a range of environmental conditions. The use of low uncertainty emissivity and low uncertainty measurement data ensured the emissivity correction was effective at reducing the differential between the thermal imager measured temperature and the surface temperature measured by a reference thermocouple in a simulated environment. This capability will aid in 3 $m^3$ box intermediate level waste container monitoring, which can only be achieved by correcting for changing conditions.

Looking ahead to further development and the deployment of thermal imagers to monitor the 3 $m^3$ store no technical roadblocks were identified.

## REFERENCES

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