HKCI: TM 4

Detection of Thermal Anomalies for Exposed Water-proof Membranes/Coatings by Infrared Thermography

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After more than ten years of implementation of TM1 ‘Detection of External Wall Debonding/Delamination by Infrared Thermography’ in 2009 (revised in 2022) and Hong Kong Laboratory Accreditation Scheme (HOKLAS) accreditation through Supplementary Criteria No. 19, there is a need about detecting thermal anomalies for exposed water-proof membranes/coatings. So in 2021, the Drafting Committee of TM4 was formed, based on the Drafting Committee of TM1, and led by Ir Dr Wallace W.L. Lai from The Hong Kong Polytechnic University. The task of the committee is to lead the drafting matters including but not limited to the practicality and implementation of another test method (TM4) on inspection of exposed and non-vertical water-proof membrane/coating by infrared thermography (IR) in built structures. Two meetings were carried out between October 2021 to September 2022. HKCI sincerely acknowledges the contribution of Ir Dr Wallace W.L. Lai for his drafting work and the aforementioned members in the Review Committee (sorted by surnames in alphabetical order) for their valuable comments.

Contents

1. Scope

1.1 This test method is to detect thermal anomalies at the test areas. Water or air retained in an exposed waterproof membranes/coating system changes its thermal resistance and the heat storage capacity. When an object of interest is to be examined, the detected thermal anomalies by this method can be used to locate possible existence of anomaly for identifying potential defect at the test areas.

1.2 This test method covers the principle, measuring apparatus, personal qualifications, testing procedures, processing and evaluation of thermograms, calibration and verification, and limitations for detecting thermal anomalies of an exposed water-proof membrane/coating on built structures by using infrared thermography (IR), in a general workflow shown in Figure 1.

1.3 Infrared detection as described in this practice is used for exposed water-proof membranes/coatings in built structures. Some examples are listed in Table 1.

Table 1 Examples of object of interest for this test method

Types	**Examples**
Structures (exposed to ambient environment)	rooftop, balcony, planter, etc
Others	emergency vehicle access, etc

The test method is not appropriate for low-emissivity materials such as metal cladding, glass, etc.

1.4 This test method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the well-trained personnel of this method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

1.5 This test method applies only to the infrared thermography survey after a water flooding/ponding as a thermal stimulus.

Request for a water tightness evaluation

Site visit and information gathering

Inspection proposal

Confirm infrared inspection and site preparation

Take and record IR thermograms

Process thermograms and prepare sketches indicating any defective areas

Inspection report

Figure 1 General workflow showing a water tightness test by IR

2. Definitions

2.1 Heat transfer occurs in three modes: conduction, convection and radiation –

Conduction – by propagation of heat energy whenever a temperature difference exists between two solid bodies in contact or among parts of a body. *Convection* – by the mass movement of gas or liquid molecules over distances. *Radiation* – a characteristic of all matter at temperatures higher than absolute zero and radiated energy may be transported over distances through gases or a vacuum with no conduction or convection medium (Maldague & Moore, 2001). Few basic heat transfer equations are shown in Appendix A.

2.2 Infrared thermography (IR) –

Acquisition and analysis of thermal radiation and its conversion to temperature from non-contact thermal imaging device (ISO, 2008). The camera collects infrared radiant energy from a target surface and produces a thermal image based on the target surface apparent temperature distribution according to Planck's law described graphically in Appendix B. IR can be used to locate seepage because water's specific heat capacity is few times higher than concrete and air.

2.3 Thermogram –

A record of a thermal image of a target surface where the user-defined grey or colour palette represent the distribution of infrared thermal radiant energy over the surface of the target (ISO, 2008).

2.4 Emissivity –

The ratio of the radiant flux emitted by a specimen to that emitted by a blackbody at the same temperature and under the same conditions (ASTM, 2022). Emissivity values range between 0 for a perfect reflector to 1.0 for a blackbody.

2.5 Heat capacity and specific heat capacity–

Ability of a material or structure to store heat. It is the amount of energy ($J\ cm^{-3}\ K^{-1}$) required to elevate by one degree a given volume of material, while specific heat capacity is equal to heat capacity per unit of mass ($J\ kg^{-1}\ K^{-1}$). Among common materials, water has one of the highest heat capacities; air, one of the lowest (Maldague & Moore, 2001).

2.6 Blackbody –

The ideal, perfect emitter and absorber of thermal radiation. It emits radiant energy at each wavelength at the maximum rate possible as a consequence of its temperature, and absorbs all incident radiance (ASTM, 2022).

2.7 Field of view (FOV) –

The total angular dimensions, expressed in degrees or radians, within which objects can be imaged, displayed, and recorded by a stationary imaging device (ASTM, 2023a).

2.8 Instantaneous field of view (IFOV) –

The smallest angle, in milliradians, that will be instantaneously resolved by a particular infrared imaging system (ASTM, 2023b).

2.9 Radian –

Angle equal to 180/π degrees or 57.29578 angular degrees (Maldague & Moore, 2001).

2.10 In this document, the following verbal forms are used (ISO/IEC, 2017):
- "shall" indicates a requirement;
- "should" indicates a recommendation;
- "may" indicates a permission;
- "can" indicates a possibility or a capability.

3. Principle

3.1 The infrared radiation is an electromagnetic wave having wavelengths ranging from 0.7 to 1000 μm. This infrared band is usually further subdivided into smaller bands including the 'near infrared (NIR)' (0.7-2 μm), the 'mid-wave infrared (MWIR)' (2-5.5 μm) and the 'long-wave infrared (LWIR)' (7-14 μm) (ISO, 2013).

3.2 Infrared thermography is based on measuring the distribution of infrared radiation (heat) emitted from a target surface. The infrared radiation is a function of object surface temperature and emissivity. Table 2 shows the emissivity values of the materials that are commonly found in this application. Table *3* shows the specific heat capacities of the corresponding materials.

Table 2 Emissivity values of different materials

Material	Emissivity
Asphalt	0.96
Bitumen	0.92
Cement	0.54
Concrete	0.92
Ethylenepropylene-diene monomer (EPDM)	0.85
Gypsum	0.93
Plaster	0.91
Polyurethane	0.57 – 0.85
Polyvinyl chloride (PVC)	0.91 – 0.93
Thermoplastic polyolefin (TPO)	0.83 – 0.86
Tile (Ceramic)	0.90 – 0.94

Sources: Maldague (2001), Transmetra (2012), Lin, Mao, Li, Li, and Wang (2021), Taylor (2019), Goddijn-Murphy and Williamson (2019), He, Zhang, and Guan (2016)

Table 3 Specific heat capacities of different materials

Material	Specific Heat Capacity (J kg^{-1} K^{-1})
Air	1005
Asphalt	920
Bitumen	1850
Cement	870 - 1040
Concrete	837
Ethylenepropylene-diene monomer (EPDM)	1800 - 2000
Gypsum	1090
Plaster	1005
Polyurethane	1800
Polyvinyl chloride (PVC)	840 - 1170
Thermoplastic polyolefin (TPO)	1700 - 1900
Water	4193

Sources: Maldague (2001), The Engineering ToolBox (2003), Lindberg, Thomas, and Christensen (1985), Shafigh, Asadi, Akhiani, Mahyuddin, and Hashemi (2020), Matmatch (2024), Kruse Training (2017)

3.3 The magnitude of the emitted radiation varies with wavelength. Wien's displacement law states that when temperature increases, the wavelength of the maximum radiation intensity decreases (Incropera & De Witt, 1990) as shown in Appendix B.

3.4 Thermal imaging device enables the emitted radiation (from an object) to be measured and displayed in the form of a visual heat image (also called 'thermogram').

3.5 If the surface finishing material contains no defects, the heat wave (e.g. generated by sun radiation on target surface) passes through uniformly into water-proof membrane/coating materials resulting in a uniform thermogram.

3.6 In case of subsurface defects (e.g. seepage), the defected areas will exhibit **abnormal temperature** than that of the area without any defects in the thermogram. These may represent potential near-surface defects. Thermal anomalies on a flat roof is shown schematically in Figure 2.

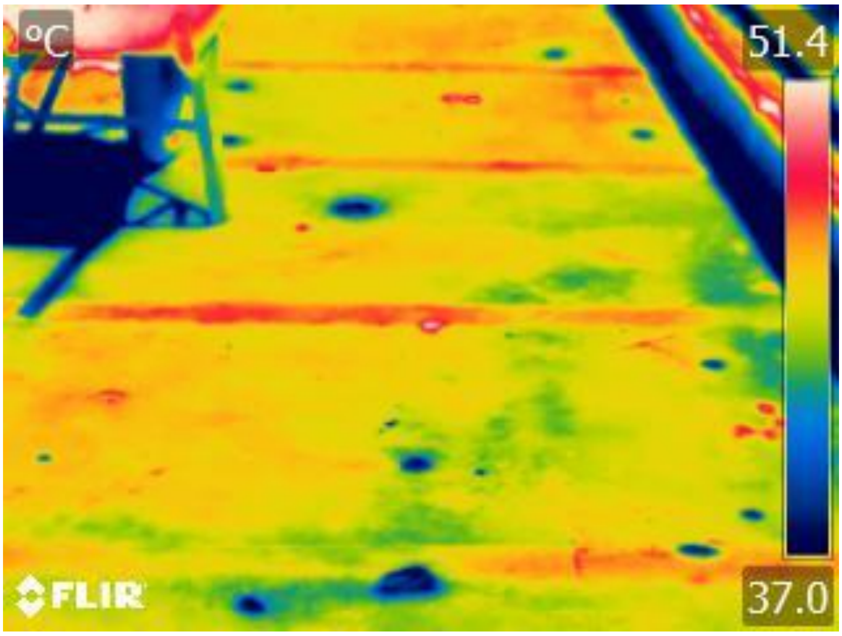

Figure 2 A typical thermogram with thermal anomalies
(Acknowledgement: Castco Testing Centre Limited)

3.7 IFOV (Instantaneous Field of View)

Instantaneous Field of View (IFOV) is an angular projection of a single detector's pixel in a thermogram and it is a measure of spatial resolution (Maldague & Moore, 2001). A schematic representation of an image segmented by IFOV is illustrated in Figure 3.

$$IFOV = \frac{FOV}{numberof\ pixels} \times \frac{3.14}{180}(1000) \quad ......[1]$$

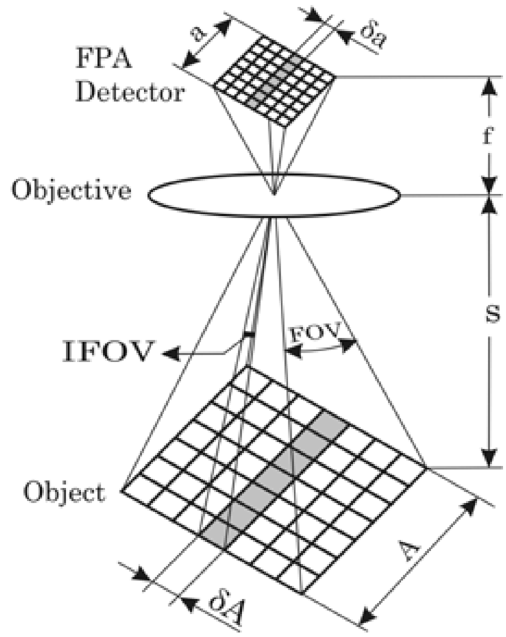

Figure 3 Definition of Instantaneous Field of View (IFOV) (Pencheva, Pulov, Gyoch, & Nenkov, 2006)

4. Measuring Apparatus

4.1 Infrared camera – An infrared imaging camera shall have a thermal resolution equal to or better than 100mK under ambient air conditions and the imaging system shall operate within a spectral range from 7 µm to 14 µm. The imaging camera shall have a spatial resolution of at most 2.5 mrad. The imaging camera shall be able to record the thermograms.

4.2 Digital camera – used for taking photographs of the actual inspection area during both walkover and aerial survey.

4.3 Angle measuring device (optional) – used for measuring angle of inclination.

4.4 Temperature measuring device (optional)

4.5 Wind speed measuring device (optional)

4.6 Relative humidity measuring device (optional)

5. Personnel Qualifications

5.1 A signatory of a test report shall either have:

(i) a valid certificate of Level 2 (or equivalent) Thermography issued by a recognised organisation operating under international standards plus at least four years of technical and managerial experience on laboratory testing in which two years are directly related to infrared thermography, or

(ii) attended and passed a training course (Appendix C) provided by a recognised tertiary institution plus at least four years of technical and managerial experience on laboratory testing in which two years are directly related to infrared thermography, or

(iii) obtained at least a higher certificate issued by a recognised technical institute or an equivalent qualification in a relevant discipline, with at least six years of directly technical and managerial experience on infrared thermography.

5.2 Testing personnel shall have the necessary qualifications, experience and technical knowledge. A testing operator shall either have:

(i) a valid certificate of Level 1 (or equivalent) Thermography issued by a recognised organisation operating under international standards plus at least one year of on-the-job experience on infrared thermography, or

(ii) attended and passed a training course (Appendix C) provided by a recognised tertiary institution plus at least one year of on-the-job experience on infrared thermography.

6. Testing Procedures

6.1 General test requirements

6.1.1 Drawings and other documents relating to object of interest such as those materials in Table 2 to be examined shall be consulted if applicable.

6.1.2 For ease of interpretation, the thermographic examination shall be carried out with constant temperature range in thermogram across the object of interest.

6.1.3 Infrared thermography work is not suitable in rainy days for outdoor environment. If thermal contrast is considered ‘inadequate’, the limitations shall be explained clearly and make reference to the limitations in Section 9.

6.1.4 Relevant factors shall be recorded prior to the survey. These factors include weather conditions, survey time, ambient temperature, relative humidity, wind speed, material type of waterproof membrane/coating, colour of waterproof membrane/coating, influence of trees shadow, and other possible factors.

6.1.5 External effects, for example heat sources installed in the object of interest shall be properly recorded or even removed before the test.

6.1.6 The object of interest to be surveyed shall be free of obstructions, for example, ponded water, debris, and piles of aggregate.

6.1.7 All outlets in the object of interest shall be sealed, and/or small plinth shall be built, if necessary, for containing sufficient water flooding/ponding to the required level for a reasonable and justifiable period of time.

6.1.8 The underside of the structure being inspected should be examined visually and relate to the locations of thermal anomalies at the exposed waterproof membrane/coating if access is possible.

6.1.9 In the case of external environment, the period of time for water flooding/ponding shall not be less than 24 hours. The IR survey shall be carried out between 24 and 48 hours after the release of water.

6.2 On-site functionality check of the thermal imaging device shall be carried out by recognizing a distinct object (e.g. fingers) clearly at five locations (middle, top, bottom, left and right) in a thermogram. At each location, adjust the focus of the camera until a satisfactory and sharp image on the object of interest is obtained.

6.3 On-site test procedures

6.3.1 Adjust the focus of the camera until a satisfactory and sharp image on the object of interest is obtained.

6.3.2 Select suitable inspection locations such that there is no or minimum obstruction between the thermal imaging device and the object of interest on to be examined.

6.3.3 The thermal imaging device shall be set and adjusted according to the directions for its use. For example, the temperature range shall be set to cover the surface temperature being studied.

6.3.4 If applicable, parameters such as emissivity (refer to Table 2), distance between the centre point of the object of interest, and ambient temperature should be properly set in the thermal imaging device before carrying out the test.

6.3.5 **Method 1 Walkover survey:** A scanning route on the object of inspection shall be recorded on the survey plan/ drawing. Thermograms on the object of interest shall be captured either by a radiometric video mode or photographic mode. The coverage of each thermogram should be within **5m** in the forward direction of the scanning route if the thermal imaging device is in the same level of the object of interest. The angle of inclination in clause 6.3.5 should be kept constant throughout the survey.

Method 2 Unmanned aerial survey by drone: Before aerial surveys are conducted, the requirement of a regulatory body on an aerial survey must be met. The test area covered in each thermogram should be less than 10m x 10m and the tilting angle should be less than 40 deg (Figure *4*). For capture of thermograms in a photographic mode, at least 20% of overlap of scanned test area should be kept between the current and the next thermograms.

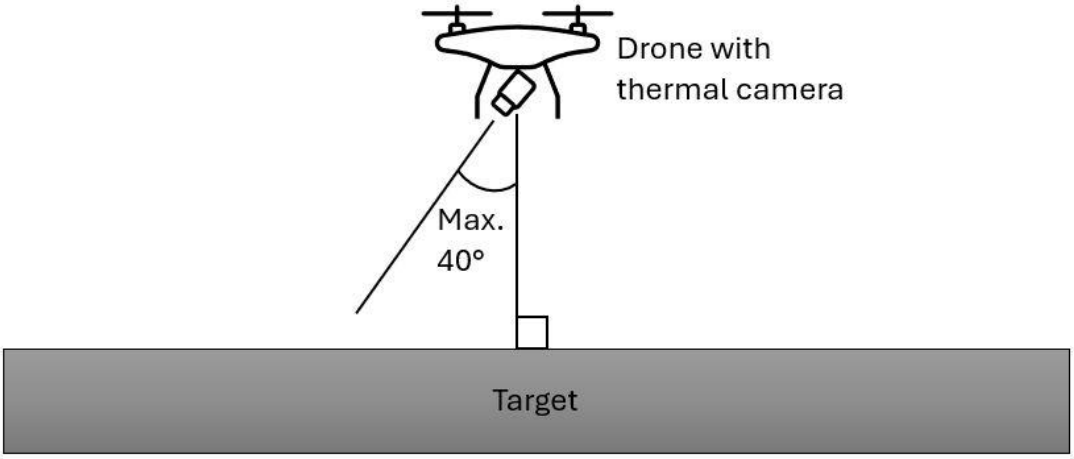

Figure 4 Requirement on tilting angle in Method 2

6.3.6 If there are more than one distinct value of emissivity or the waterproof membrane/coatings are visually different, the thermograms shall be separately captured.

6.3.7 In order to determine whether the temperature variation detected is from the seepage or due to the reflection from another surfaces, it is necessary to study the surface from different positions to eliminate the possibility of mis-interpretation due to reflections from other surfaces. If necessary, take thermograms of the object of interest from a position in adjacent or higher location.

6.3.8 All thermograms and the respective locations, regardless any patches of relative abnormal temperature zone(s) are detected or not, shall be recorded with/without the aid of adjacent permanent structures. All suspected water-trapped patches shall be checked by the test operator if the object of interest is accessible. Further detail verification in Section 13 of ASTM (2023b)should be adopted.

6.3.9 Take ordinary photographs at the same locations where thermograms have been taken.

7. Processing and Evaluation of Thermograms

7.1 Any ‘abnormal’ temperature distribution shall be noted in the grayscale/colour palette of temperature which shall be **evenly/linearly distributed** to represent the temperature at each pixel for not causing biases during interpretation. The chosen span of the maximum and minimum temperatures of the temperature bar in any thermogram should be **smaller than/equal to** the maximum and minimum of temperature values recognized within the objects of interest. Temperature values of other objects outside the objects of interest, e.g. drain cover, metal grille, floor drain, shall be excluded in the said span.

7.2 The ‘abnormal’ temperature distribution, or thermal anomalies may be caused by:
- defective waterproof membrane/coatings;
- infrared radiations from nearby sources;
- moisture or debris or surface emittance on the inspected surface; and
- known or unknown variations within the waterproof and roofing structures, for example, type/thickness of thickness, density, continuity, moisture content, type/thickness of aggregate surfacing, roof deck and supporting structure, inconsistencies in the waterproofing system due to damage, repairs, coatings or overlays, temperature beneath the roofing system.

7.3 An example of a proper thermogram is demonstrated in Figure 5.

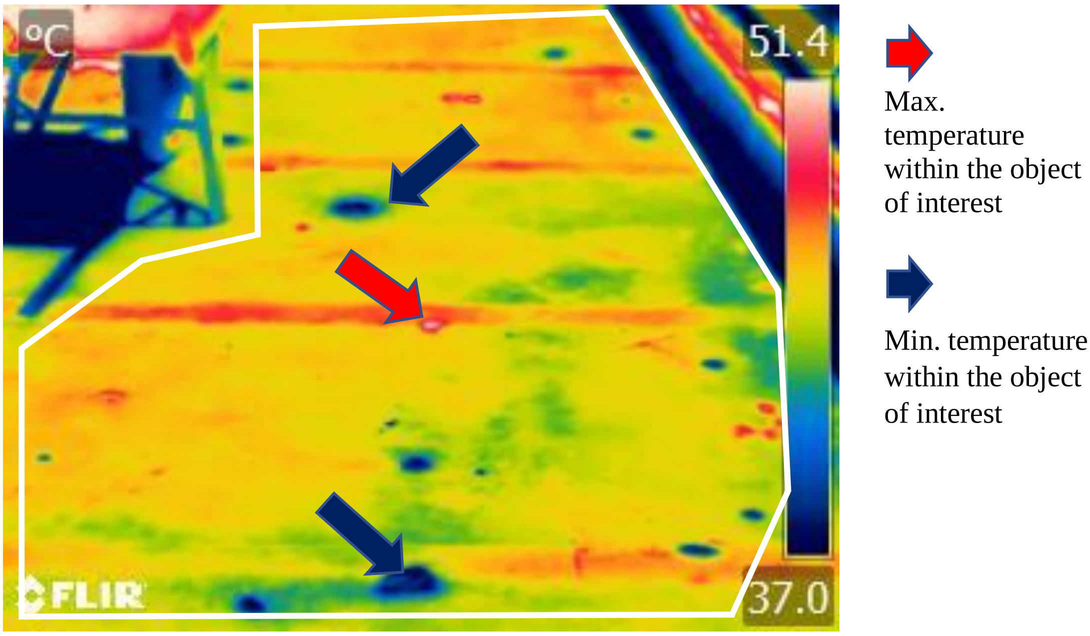

Figure 5 A thermogram satisfying the conditions as required in Section 6.3 and 7.1 (maximum and minimum temperatures of the evenly/linearly distributed temperature bar in the object of interest highlighted in the white frame) (Acknowledgement: Castco Testing Centre Limited)

7.4 Qualitative evaluation

To evaluate the thermographs, drawings, other construction documents relating to the waterproof membrane/coating and the relevant photographs can be employed. In addition, the following factors shall be considered:

7.4.1 the weather conditions, ambient temperature;
7.4.2 wetting of rooftop surface or moisture content within the waterproof membrane/coating;
7.4.3 existence of any heat generating plants machines behind the roof;
7.4.4 emissivity of the objects of interest;
7.4.5 reflectance of the objects of interest;
7.4.6 roughness or unevenness of the objects of interest;
7.4.7 stains on the objects of interest;
7.4.8 colour of the objects of interest;
7.4.9 angle of view and survey distance;
7.4.10 construction of the objects of interest;
7.4.11 building in shade of eaves or adjacent buildings; and
7.4.12 screening objects (e.g. trees, debris, metal objects, ventilation facilities).
7.4.13 factors described in Section 7.2.

8. Calibration and verification

Calibration of the equipment shall be performed according to Table 4.

Table 4 Calibration/verification requirements of a thermal imaging device

Type of equipment	**Recommended maximum period between successive calibration/verification**	**Recommended calibration/verification procedure or guidance documents and equipment requirements**
Infrared imaging device	5 years	Calibrate using reference black bodies. The calibration certificate of an infrared imaging device shall contain sufficient information especially reference temperature values, measured temperature values taken by the thermal imaging device and percentage of errors.
	1 year	Carry out the uniformity check of every image pixel of a thermal imaging device on a flat target with a high emissivity (at least 0.9). The check shall be carried out in at least three distinct and controlled temperature values which are within the working range of the thermal imaging device. If the statistical error(s) of the temperature distribution is larger than the value recommended by the manufacturer, a full calibration/repair of the thermal imaging device is necessary.
	Before each test	Check the working performance of the thermal imaging device for detection of temperature variation.

9. Limitations

9.1 Only surface temperatures of object of interest are detected.
9.2 Table 5 lists commonly found limitations on measurements by infrared thermography:

Table 5 Limitations of an infrared thermography survey

Limitations	Examples	Reasons of declaring 'Survey Unreliable'	Reasons of declaring 'Survey not Successful'
A. Reflections from other sources	Accurate temperature measurements are hindered by different emissivities and reflections from other sources, such as other heat sources, building features, stains on the object of interest, uneven surfaces.	Applicable	Applicable
B. Insufficient thermal contrast	No sufficient temperature differences over the surface of object of interest	Applicable	Applicable
C. Unable to gain access	There is no accessible passageway for (1) conducting the survey, or (2) checking of suspected water-trapped patches according to section 6.3.8, e.g. narrow alleyway, or such accessible passageway is located in a private area which need access permission from the owners.	Applicable	Applicable
D. Unknown variations within the waterproof and roofing structures as suggested in Section 7.2	Type/thickness of thickness, density, continuity, moisture content, type/thickness of aggregate surfacing, roof deck and supporting structure, inconsistencies in the waterproofing system due to damage, repairs, coatings or overlays, temperature beneath the roofing system.	Applicable	Applicable
E. Tilting angle	The tilting angle for taking data is larger than 40°.	Applicable	Applicable

10. Reporting

10.1 General

The test report shall contain the following information when available or applicable:

- Project name and test locations
- Client's information
- Objects of interest with reference to Table 1 (e.g. material, location, any obstruction nearby…)
- Time at which water flooding is started

- Time at which release of water is completed
- Height of water level for water flooding, if applicable
- Type of waterproof membrane / coating
- Date and time of infrared thermography survey
- Information of the thermal imaging device used
- Any moisture or obstructions present on the waterproof membrane / coating at the time of the infrared thermography survey
- Name of operator and approving personnel

10.2 Details

The test report shall contain the following details:

- Temperature bar shall be displayed in each thermogram according to Clause 7.1
- Weather condition including precipitation, ambient temperature and wind speed during the IR inspection
- Scope of IR inspection
- Identification of the waterproof membrane/coating surveyed
- Sketches or elevations showing the IR inspection results
- Limitations and any supplementary information of the inspection
- Appendix including relevant thermograms, photographs, reference documents, etc.

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Appendix A Heat Transfer Equations

1. Heat transfer is also influenced by the change of material thermal characteristics (density, thermal capacity and conductivity).

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad \text{(3-Dimensional heat conduction)....[2]}$$

where T is temperature (K), t is elapsed time, x, y, and z are heat transfer directions and $\alpha = \frac{k}{C\rho}$ is thermal diffusivity (m^2/s).

2. The 3-dimensional heat conduction in the rooftop is interrupted when there are seepage present in surface cracks/joints/fractures. Thermal anomalies can be detected due to the cooling/heating effect of water circulating within the cracks/joints/fractures; different thermal transfer capacity of the infilling material with respect to the rooftop).

$$C\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) \quad \text{(heat conduction)....[3]}$$

which is a general form of equation [3] where C is specific heat (J kg^{-1} K^{-1}), ρ is density (kg m^{-3}), k_x, k_y, k_z (W m^{-1} K^{-1}) are the anisotropic thermal conductivities of heat transfer in the material in the x, y, and z directions.

3. An ideal object whose emissivity is 1.0 is called a 'black body'. Planck's law describes the spectral distribution of the radiation from a blackbody by means of the following equation (DeWitt & Nutter, 1988):

$$L'_{\lambda,b} = \frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}[W/m] \quad \text{... ... [4]}$$

Where

$L'_{\lambda,b}$ is the blackbody spectral radiant emittance at wavelength λ;
c is the velocity of light (3 x 10^8 m/s);
h is Planck's constant (6.6 x 10^{-34} J S);
k is the Boltzmann's constant (1.4 x 10^{-23} J / K);
T is the absolute temperature (in K) of a blackbody;
Λ is the wavelength (in m).

Appendix B Spectral radiance of a blackbody and graybody under Planck’s law

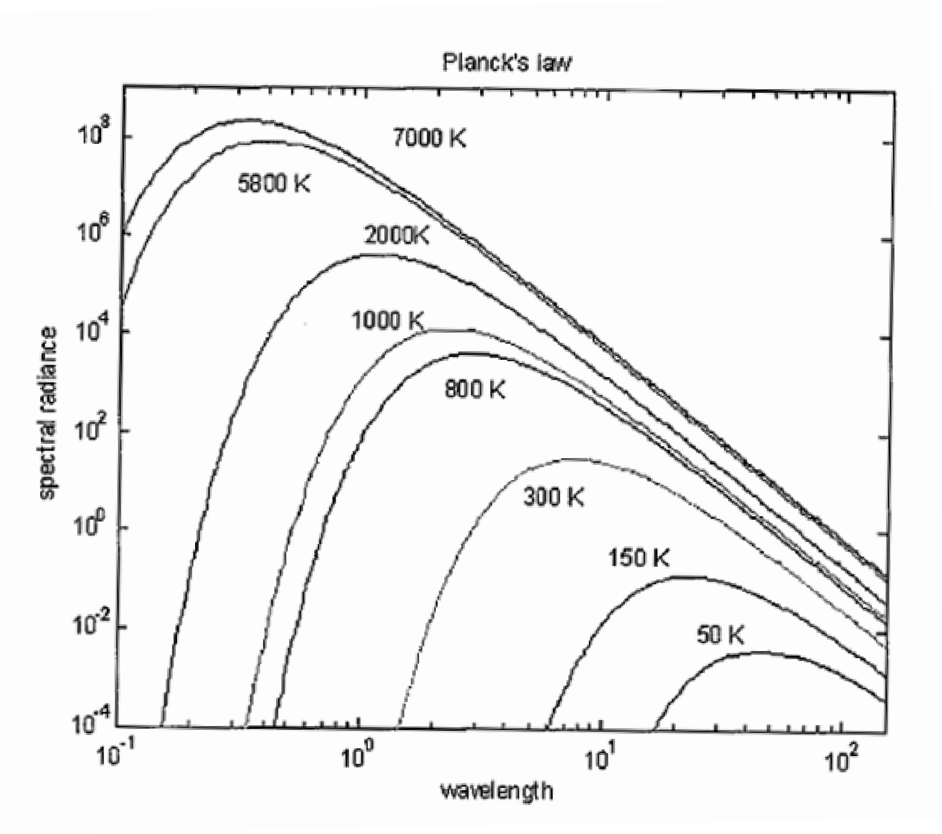

Figure 5 Spectral radiance of a blackbody based on Planck's law

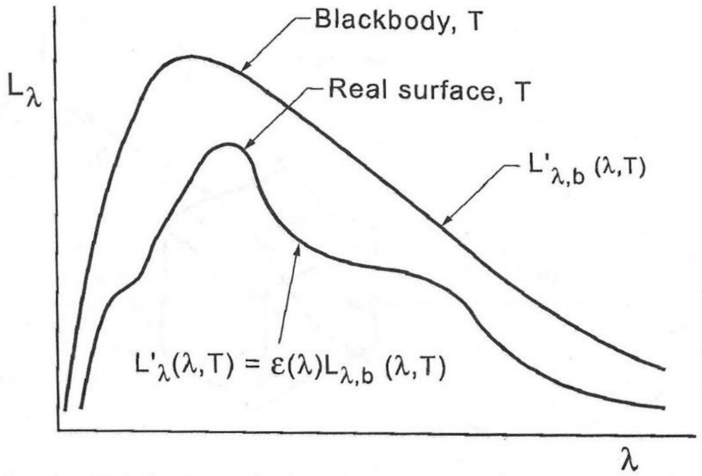

Figure 6 Spectral radiance of a greybody based on Planck's law

Appendix C Requirements on Infrared Thermography training course

1. A typical training course on Infrared Thermography shall span a duration of a minimum of 27 teaching hours, and shall comprise the following: -

   A. Lecture

      1. Infrared theory / radiosity
      2. Heat transfer principles
      3. Characteristics of infrared camera
      4. Calibration and uniformity check of infrared camera
      5. Thermogram analysis

   B. Practical (not less than 9 hours)

      1. Practical exercise on the use of infrared camera for building diagnosis and water tightness test
      2. Computer aided data analysis of thermograms
      3. Interpretation of test results

   C. Assessments

      1. Coursework
      2. Practical assessment
      3. Written assessment

2. A typical training course on Infrared Thermography shall span a duration of a minimum of 15 teaching hours, and shall comprise the following: -

   A. Lecture

      1. Basic principle and theory of infrared thermography
      2. Operation of infrared camera
      3. Uniformity check of infrared camera (including sources of error)

   B. Practical (not less than 9 hours)

      1. Practical exercise on the use of infrared camera for building diagnosis and water tightness test
      2. Uniformity check of infrared camera

   C. Assessments

      1. Coursework
      2. Practical assessment
      3. Written assessment