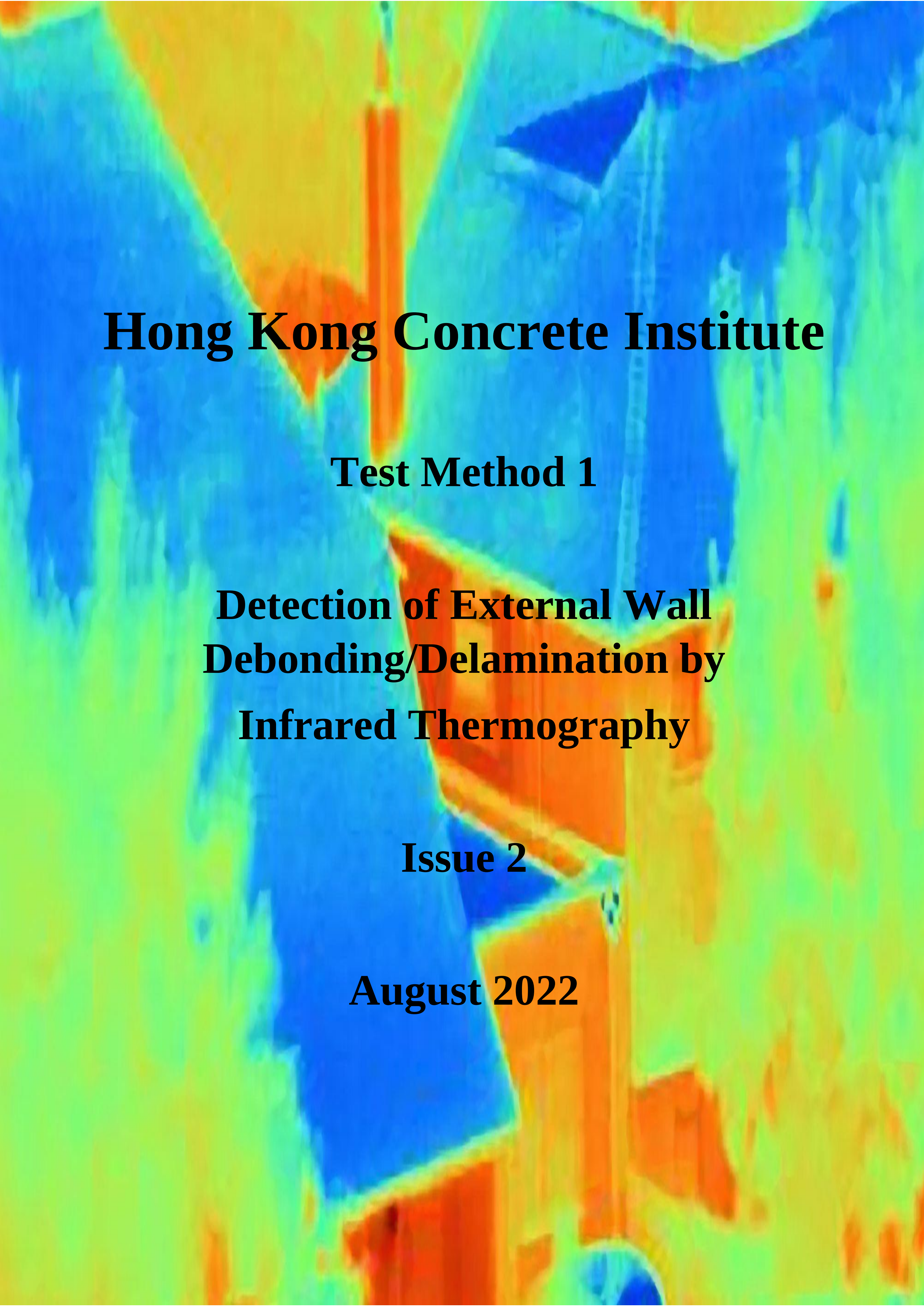

Hong Kong Concrete Institute

Test Method 1

Detection of External Wall Debonding/Delamination by Infrared Thermography

Issue 2

August 2022

HKCI: TM 1

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Drafting work led by The Hong Kong Polytechnic University

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After more than ten years of implementation of TM1 and Hong Kong Laboratory Accreditation Scheme (HOKLAS) accreditation through Supplementary Criteria No. 19, the Review Committee is formed by Ir Dr Wallace W.L. Lai from The Hong Kong Polytechnic University in July 2021 to lead the review matters including but not limited to the practicality and implementation of TM1. The committee is formed by the practitioners of the infrared thermography method on debonding inspection, and four meetings were carried out between July to Oct 2021. HKCI sincerely acknowledges the contribution of Ir Dr Wallace W.L. Lai for his drafting work and the following members in the Review Committee (sorted by surnames in alphabetical order) for their valuable

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Contents

1. Scope

1.1 This test method covers the equipment, field procedures, and interpretation of thermograms for determining the potential debonding/delamination of exterior wall finishes of a building by using infrared (IR) thermography, in a general workflow shown in Figure 1.

1.2 Infrared measurements as described in this practice are used for external wall finishes such as rendering, tiles and fair faced concrete, etc. The test method is not appropriate for low-emissivity materials such as metal cladding, glass, etc.

1.3 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.

1.4 This test method does not apply to the determination of the degree of thermal insulation, air tightness of a building, and measurement of the absolute temperature of an object.

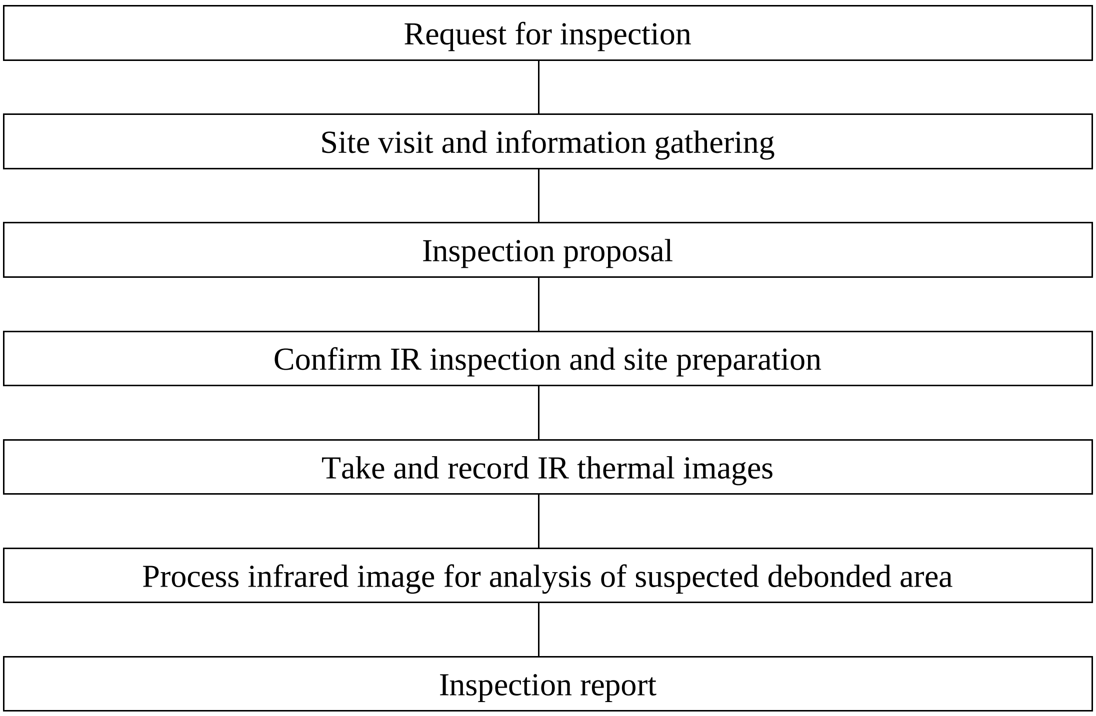

Figure 1 General workflow showing a diagnosis of IR inspection for external wall finishes

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 large distances.
Radiation – a characteristic of all matter at temperatures higher than absolute

zero and radiated energy may be transported over large 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 –

Acquisition and analysis of thermal radiation and its conversion to temperature from non-contact thermal imaging camera (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 delamination or debonding but not differentiate among these two defects.

2.3 Thermogram –

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

2.4 Delamination –

Laminar discontinuity is generally an area of un-bonded layers of a material, as shown in Figure 2 (Maldague & Moore, 2001).

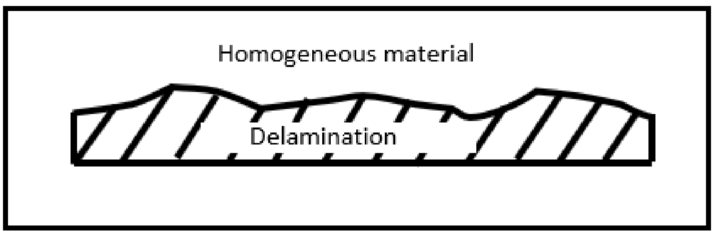

Figure 2 A delamination in a homogeneous material

2.5 Debonded area –

The air space within a finishing mortar or tile of an external wall or any structural surfaces made of any composite materials (Maldague & Moore, 2001). Delamination and debonded area are not distinguishable in infrared thermography survey, as shown in Figure 3.

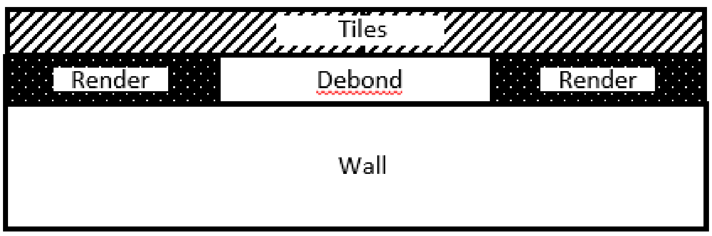

Figure 3 A debonded area in a composite material

2.6 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, 2019). Emissivity values range between 0 for a perfect reflector to 1.0 for a blackbody.

2.7 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, 2019).

2.8 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, 2015a).

2.9 Instantaneous field of view (IFOV) –

The smallest angle, in milliradians, that will be instantaneously resolved by a particular infrared imaging system (ASTM, 2015b).

2.10 Radian –

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

2.11 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 (IR) 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 1 shows the emissivity values of the materials that are commonly found in this application.

Table 1 Emissivity values of different materials

Material	Emissivity
Asphalt	0.96
Basalt (Rough)	0.93
Concrete	0.92
Feldspar	0.87
Granite	0.82
Lime	0.3 – 0.4
Marble (Grey, Polished)	0.93
Paint (Oil-based)	0.92 – 0.98
Plaster	0.91
Red brick	0.93
Tile (Ceramic)	0.90 – 0.94

Source from: *Theory and practice of infrared technology for non-destructive testing* (Maldague, 2001), *Table of Emissivity of Various Surfaces For Infrared Thermometry* (Transmetra, 2012)

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 IR camera 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 the external wall resulting in a uniform thermal image.

3.6 In case of subsurface defects (e.g., debonding), the defected areas will exhibit higher temperature than that of the area without any defects under the heating from the sun and creating hot or warm spots in the thermogram, although higher temperature may also be caused by other sources like reflection, as well as nearby and/or hidden hot devices. These may represent potential near surface defects. A diagnosis of IR inspection for external wall finishes is shown schematically in Figure 4.

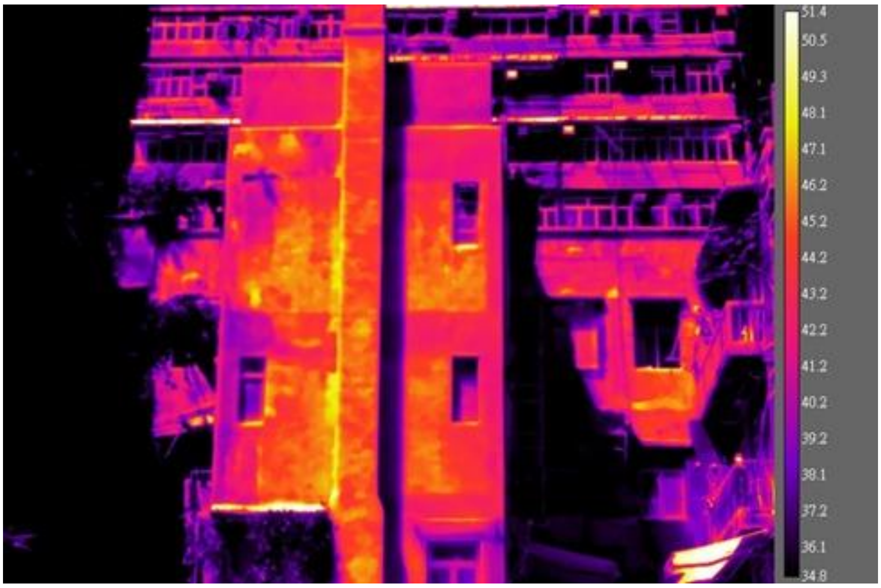

Figure 4 A typical thermogram with defects (Acknowledgement: Fugro (Hong Kong) Limited)

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 5.

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

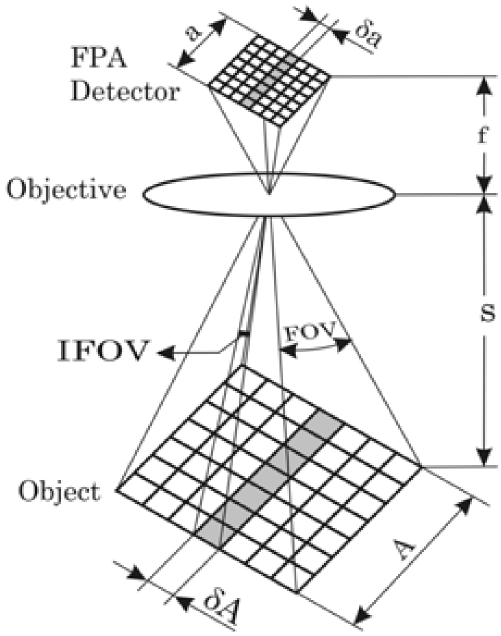

Figure 5 Definition of Instantaneous Field of View (IFOV) (Pencheva, Pulov, Gyoch,

& Nenkov, 2006)

4. Measuring Apparatus

4.1 Infrared camera – An infrared imaging device shall have a thermal resolution of not less than 0.1℃ under ambient air conditions and the imaging system shall operate within a spectral range from 7 μm to 14 μm. The imager shall have a spatial resolution of at most 1.3 mrad. The imaging device shall be able to record the thermal images.

4.2 Zoom lens – used with IR camera mentioned in Clause 4.1 to provide continuous variation of the magnification of the image or zoom lens of suitable magnification factors.

4.3 Digital camera – used for taking photographs of the actual inspection area.

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

4.5 Temperature measuring device (optional)

4.6 Wind speed measuring device (optional)

4.7 Relative humidity measuring device (optional)

5. Personnel Qualifications

5.1 A signatory[1] 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[2] 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 the building envelope to be examined shall be consulted if applicable. Prior to the actual inspection, on-site walkover survey is preferable.

6.1.2 For ease of processing and evaluation, the thermographic examination shall be carried out with constant temperature across the building envelope.

6.1.3 Infrared thermography work is not suitable in rainy/cloudy days and days with high wind speed. It is only suitable under fine weather (according to Hong Kong Observatory, fine weather is defined as the sky covered by a total cloud amount of less than six eighths), low wind speed (not higher than 6.5 m/s). Fine weather condition should last for at least 12 hours prior to the survey aiming for adequate **thermal contrast** (materials-, equipment- and weather-dependent) on the object of interest. If thermal contrast is considered 'inadequate' due to the limitation(s), such limitations shall be explained and recorded clearly. Some commonly found limitations are stated in Section 9 of this document.

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 finishes, color of finishes, influence of trees shadow, distance between the building and IR camera, and other possible factors.

6.1.5 External effects, for example heat sources installed in the building, should be properly recorded or even removed before the test.

6.2 Before performing an IR inspection, an on-site functionality check of the IR camera 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 IR camera until a satisfactory and sharp image on the object of interest is obtained.

6.3.2 Select suitable inspection locations outside the building such that there is no or minimum obstruction between the IR camera and the external wall to be examined.

6.3.3 The IR camera 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 1), distance, ambient temperature shall be properly set in the IR camera before carrying out the test.

6.3.5 Set up and adjust the IR camera to an optimal focus distance and view angle in accordance with the manufacturer specification. Generally, the angle of inclination should be **less than 40 deg**. Relocation of the IR camera should be made, if required.

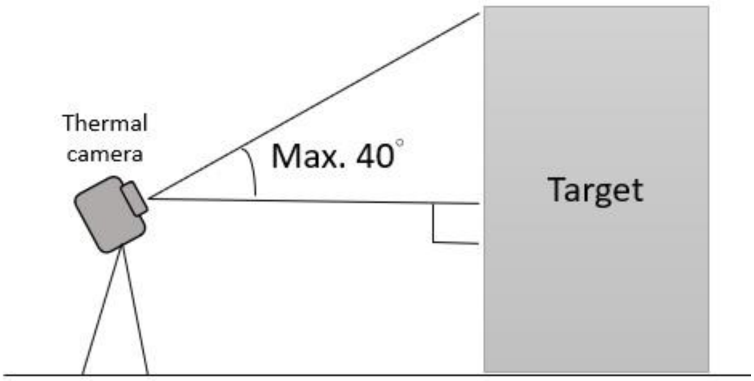

Figure 6 Requirement on angle of inclination

6.3.6 Start the inspection by performing a preliminary inspection over the wall surface.

6.3.7 Parts of the surface of special interest (e.g. anomalies) shall be inspected in detail using a zoom lens (specified alongside the thermogram in the report).

6.3.8 Take thermograms for the selected part of wall surface with the same estimated emissivity in Section 6.2. If there are more than one distinct value of emissivity or the wall finishes are visually different, the thermograms shall be separately captured.

6.3.9 Each IR thermogram should include **not more than four to five storeys** of a building. If required, a zoom lens should be used or relocation of the IR camera should be made so that the necessary view image is captured. A robotic device, e.g. Unmanned Aerial System (UAS), with the radiometric IR camera fulfilling the requirements of equipment in this document, may also be used to fulfil the requirement and improve image resolution according to Clause 6.3.2 and 6.3.5.

6.3.10 In order to determine whether the temperature variation detected is from the defect or due to the reflection from other surfaces, it is necessary to study the surface from different positions to eliminate the possibility of misinterpretation due to reflections from other surfaces.

6.3.11 If necessary, IR thermograms should be taken from a position adjacent to or at higher location(s) for the upper portion of the building to be inspected.

6.3.12 Ordinary photographs shall be taken 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 shall be **smaller than** 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. windows, louvre, shall be excluded in the said span.

7.2 An example of proper thermogram is demonstrated in Figure 7, satisfying the conditions required in Section 6.1.3, 6.3.5, 6.3.9 and 7.1

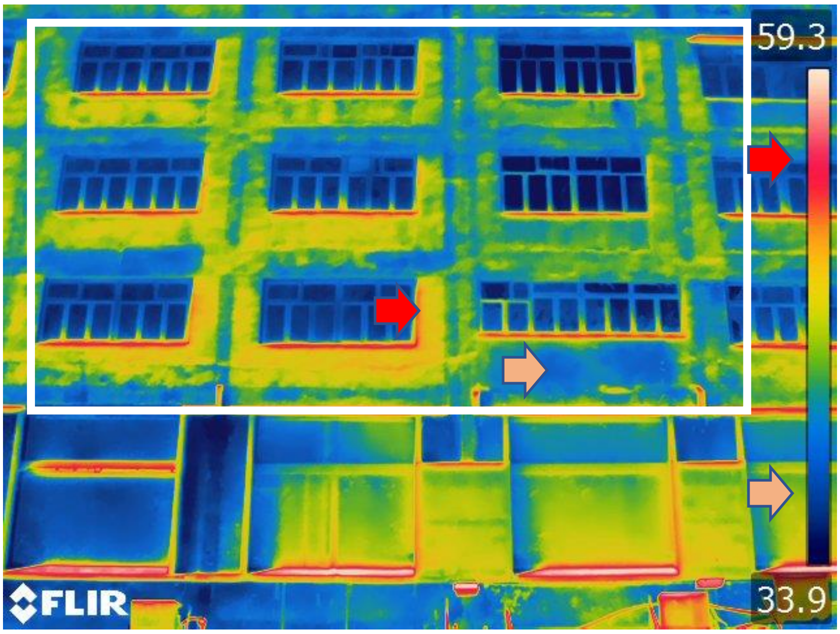

Figure 7 A thermogram satisfying the conditions required in Section 6.1.3 (fine weather condition), 6.3.5 (angle of inclination less than 40 deg), 6.3.9 (not more than four to five storeys) and 7.1 (maximum and minimum temperatures of the evenly/linearly distributed temperature bar in the object of interest highlighted in the white frame)

7.3 Qualitative evaluation

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

7.2.1 the weather conditions, ambient temperature;
7.2.2 wetting of wall surface or moisture content within the wall;
7.2.3 orientation of building to the path of sunshine during the inspection;
7.2.4 existence of any heat generating plants machines behind the wall;
7.2.5 emissivity of wall surface;
7.2.6 reflectance of wall surface;

7.2.7 roughness or unevenness of wall surface;
7.2.8 stains on wall surface;
7.2.9 colour of wall surface;
7.2.10 angle of view and survey distance;
7.2.11 construction of wall finishing;
7.2.12 building in shade of eaves or adjacent buildings; and
7.2.13 screening objects (e.g. trees and signs).

8. Calibration and verification

Calibration of the equipment shall be performed according to Table 2.

Table 2 Calibration/verification requirements of an infrared camera

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 infrared imaging device and percentage of errors.
	1 year	Carry out the uniformity check of every image pixel of an infrared 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 infrared 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 infrared imaging device is necessary.
	Before each test	Check the working performance of the infrared imaging device for detection of temperature variation.

9. Limitations

9.1 Only surface temperatures of external wall finishes are detected.
9.2 Table 3 list commonly found limitations on measurements by infrared thermography:

Table 3 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 wall surfaces, sign of water seepage.	Applicable	Applicable
B. Insufficient thermal contrast	External wall finishes, not adequately exposed to direct sunlight or obstructed by solid objects (such as service ducts, facilities, or others).	Applicable	Applicable
C. Unable to gain access	There is no accessible passageway to reach the target, e.g. narrow alleyway, or such accessible passageway is located in a private area which need access permission from the owners.	Not Applicable	Applicable
D. Angle of inclination	The angle of inclination for taking data on upper floors is larger than 40°.	Not 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
- Name of operator and approving personnel
- Date and time of inspection
- Information of IR equipment used
- Description of the test surface

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 walls 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).

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$ (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 external wall is interrupted when there are surface cracks/joints/fractures. Thermal anomalies can be detected due to the cooling/heating effect of air circulating within the air gap (delamination/debond); different thermal transfer capacity of the infilling material with respect to the external wall).

$$C\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)$$ (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):

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

Where

$L'_{\lambda,b}$ is the blackbody spectral radiant emittance at wavelength λ;
c is the velocity of light (3×10^8 m/s);
h is Planck's constant (6.6×10^{-34} J S);
k is the Boltzmann's constant (1.4×10^{-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

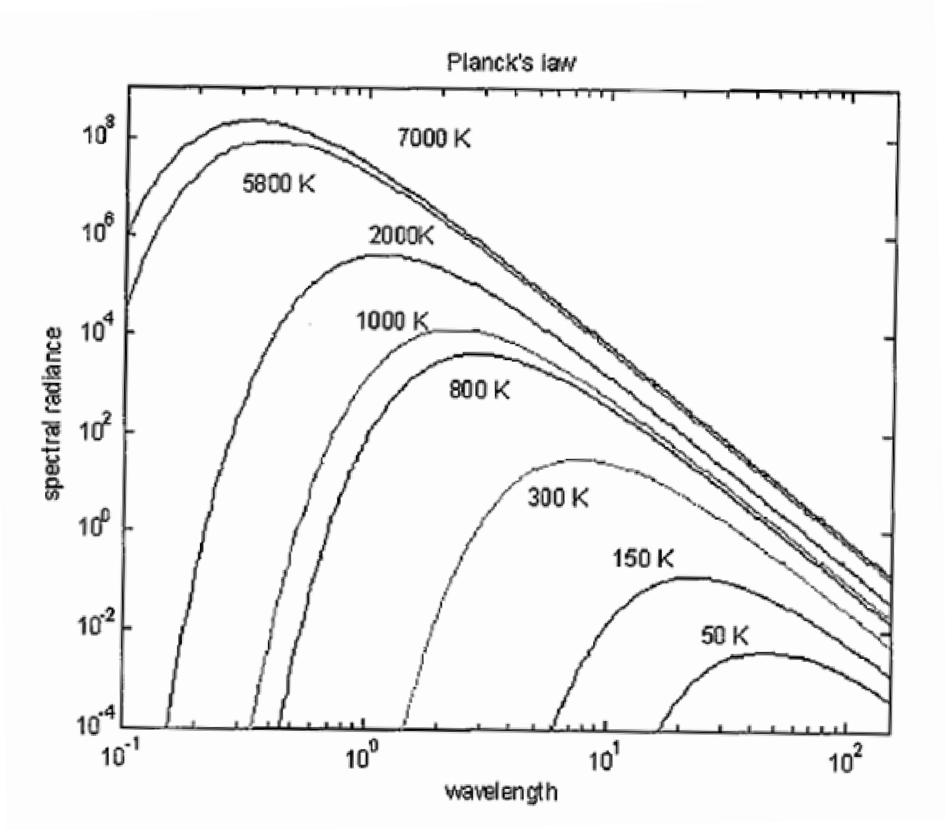

Figure 8 Spectral radiance of a blackbody based on Planck's law (Maldague, 2001)

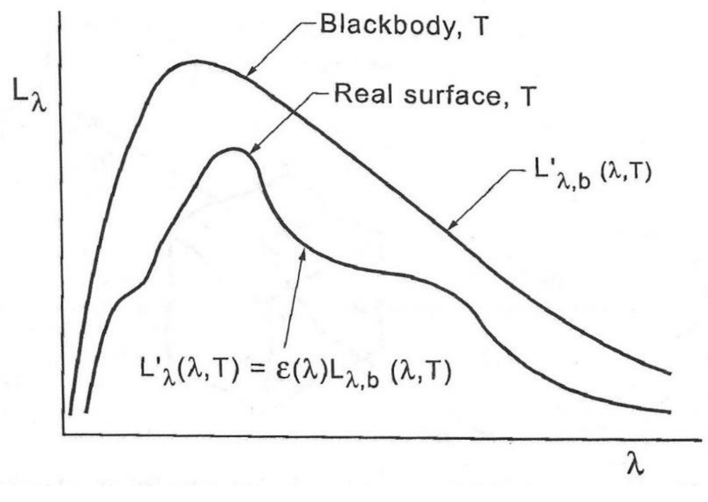

Figure 9 Spectral radiance of a greybody based on Planck's law (Maldague, 2001)

Appendix C: Requirements on Infrared Thermography training course

1. A typical training course on Infrared Thermography for Signatory stated in Section 5.1 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. Thermal image analysis

   B. Practical (not less than 9 hours)

      1. Practical exercise on the use of infrared camera for building diagnosis
      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 for Testing personnel stated in Section 5.2 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
      2. Uniformity check of infrared camera

   C. Assessments

      1. Coursework
      2. Practical assessment
      3. Written assessment