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UNCERTAINTY IN THERMOGRAPHIC NON-DESTRUCTIVE TESTING

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ABSTRACT

This report is part of the End to End digitised testing theme in the advanced engineering materials NMS program. It builds on the work of the previous year's NMS to assess the development of uncertainty budgets for measurements for thermographic non-destructive testing, give guidance on where this could be improved and areas that require further study to develop robust uncertainty budgets for these measurements.

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Approved on behalf of NPLML by
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GLOSSARY

AEM	Advanced Engineering Materials
BVID	Barely Visible Impact Damage
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NMS	National Measurement System
POD	Probability Of Detection
TBC	Thermal Barrier Coating
TSR	Thermographic Signal Reconstruction

1 INTRODUCTION

This work is part of the end-to-end Digitised Materials Testing and Verification theme of the National Measurement System (NMS) work in the Advanced Engineering Materials (AEM) group. It was formulated to assess the position of uncertainty determination in non-destructive testing (NDT) and generate frameworks for different NDT methods that can be applied digitally to enhance the quality of measurements.

One of the methods chosen to focus on in this NMS year is thermography. Thermographic NDT is the term used to describe the monitoring of a material or component with a thermographic camera. The method essentially looks for differences in the surface temperature of an object that can be attributed to a disruption of heat flow through a sample. This disruption of heat flow may be due to a difference in the material at that position and can be used to infer the presence of a defect.

When monitoring temperatures in thermographic NDT, an infrared camera is used that records the temperature at every pixel in the image. This raw data is built up into a relative intensity image by the thermal camera software. The relative intensity images can be used in a comparative way to assess the presence of defects by comparing defect free areas to the areas of difference in the image. The raw data that is gathered for each pixel can also be assessed through time to estimate the depth of a defect in a sample as an input of heat propagates through the sample as a thermal wave and interacts with deeper defects at later times. However, this the estimation of depth using the measurement of absolute temperature is only achievable for some thermography measurements, not all thermographic NDT.

Although a very useful technique for screening of materials and components, it presents difficulties for inspectors since obtaining a reliable measurement is challenging and to an extent is largely dependent on the skill of the operator. Various factors can have a large effect on the success of a measurement such as the surface finish, thickness, depth of defects, lateral size of defects, through thickness extent, sample curvature and the orientation of the excitation source and camera to the sample.

1.1 THERMOGRAPHIC NDT IN AN INDUSTRIAL CONTEXT

A previously published NPL report explored some of the reasons as to why there is a requirement for uncertainty in measurements and also why there is resistance to this within the NDT industry [1]. The requirement for uncertainty in test reports is a result of needing to meet the quality standards for accreditation as a testing laboratory. This is required for cases such as minimum allowable thickness and maximum allowable defect size, but often clashes with the culture of the NDT industry as a whole. Generally in industry, a defect is required to be found with a certain degree of confidence and the general size of the defect is of interest but detailed sizing of the defect is not always necessary.

This has led to the use of the concept of probability of detection (POD) as a more relevant benchmark for NDT. This concept establishes the capability of a technique to detect a flaw of a given size and usually takes the form of a curve plotting the probability that a defect will be detected against the size of that defect. This works well for parts of industry that carry out lots of repeat tests on the same components but is less effective for more ad hoc measurements where this statistical style data is not available. Studies have been carried out to determine the probability of detection of defects with thermography [2].

All NDT methods to some extent are dependent on the skill and experience of the operator but thermography is perhaps one of the most dependent on these factors in terms of knowledge of how surface conditions of a sample and the ambient atmosphere in general can affect a measurement.

Typically, active thermographic NDT [3] where the method includes an active source of heating to input the required energy to assess a part is used in a qualitative rather than quantitative fashion by the NDT industry. This has meant that the demand for uncertainty determination in everyday testing using

this method has been low. Much research has therefore focussed on improving the detectability of defects or the application to specific parts and inspection scenarios [4].

The focus on qualitative data arises since it has generally been accepted that there are limits to the ability to carry out these inspections with high repeatability. This is due to a range of factors including the surface finish, material properties and geometry of samples and variations in atmospheric temperature especially when testing components in situ [5]. As such any assessment of uncertainty or probability of detection of defects needs to be carried out on a case-by-case basis.

A study of the treatment of uncertainty in the sector has been carried out here by assessing the scientific literature available in the subject. This has shown a focus on the temperature measurement carried out in a passive measurement. This is understandable since it is the most quantifiable application due to the uncertainty in the imager being the dominant factor. However, further work is apparent in the literature on both flash thermography and on the processing of data in image and absolute temperature form in order to obtain quantitative measurements.

Methods using the long pulse and lock in techniques are not in general rigorously assessed in the literature due to the less quantifiable nature of measurements. This makes it more difficult to provide meaningful uncertainties for the relevant quantities of interest. As such they are considered here in the context of how uncertainties could be applied to them and any additional uncertainties that arise for them based on the different application of the technique.

Quite apart from the growing requirements to provide uncertainty budgets for measurements in order to achieve the relevant certifications as testing laboratories, the desire for an assessment of uncertainty in measurement will increase as industry moves through industry 4.0 and the NDT industry respectively moves through NDE 4.0. These changes will generate and process much more data and move the human influence away from the inspection and interpretation itself. Beginning to think about the uncertainty in the raw data as it is collected and how this flows through to the stored images or data from the component will be important.

1.2 TYPES OF THERMOGRAPHIC NDT

Thermographic NDT can be broadly split into different categories these are differentiated by whether they use an active heating pulse, how long this pulse is applied for and the degree of synchronisation between the source and the detector.

- Passive thermography – the temperature of a surface is passively monitored using a thermal camera. This is often used in condition monitoring of machinery and components to ensure there are no changes to operation that would indicate activity out of operational tolerance. The change in temperature provided by the heating and cooling is uncontrolled e.g., heating of a structure through solar heating or heating of components by the internal processes, for example steam in plant pipework.
- Flash thermography –Involves the excitation of a sample using a high power millisecond duration flash. This can be used to obtain quantitative data, since the input energy can be treated as an impulse and is therefore treated as complete before the measuring phase of an experiment begins.
- Long pulse thermography involves the use of flood lamps or heat guns to apply a longer duration heat excitation (of the order of 10s of seconds duration) this generates an indication of the presence of a defect but in general the size and depth can’t be well quantified.
- Lock in thermography is a variation of thermography that involves the periodic input of energy to a sample (at NPL this is achieved using flood lamps, but it is possible with a wide range of other excitation methods). By measuring the phase of the surface temperature compared to the input wave, internal defects can be highlighted. If there is a good knowledge

of the material properties, then the lateral size and depth of the defects can be estimated. These measurements take longer than other thermal techniques and the resolution of the defects will reduce due to heat diffusion, if they are found deeper through the sample.

1.3 OTHER EXCITATION METHODS

Other methods of thermography are available in addition to these more traditional optical methods. These are mentioned here for completeness, but they are not currently available to be used at NPL and will therefore not be considered in detail. The current capability at NPL in materials characterisation lies in flash, long pulse, lock in and passive thermography such that these are the methods of interest in this work.

Vibrothermography [6]– an ultrasonic transducer operating in the range between 20 to 45kHz is used in contact with a sample to introduce a vibration. This vibration propagates through a part to a crack and causes the surfaces of the crack to rub together, generating friction and resulting heat that can be detected by a thermal camera. This type of thermography is most suited to metallic structures with surface or near surface microcracking.

Eddy current thermography [7] requires a conductive material that is excited with a high frequency AC current. Defects such as cracks, voids and delaminations alter the eddy current distribution around the defect, changing the heating caused by the joule effect, and can be detected by a thermal camera.

It is important to emphasise here that thermographic NDT greatly benefits from an expert operator. Many issues that are encountered with the use of thermography are due to its use in applications for which it is not suited. For example, in the above, vibrothermography and eddy current thermography are effective for crack detection due to the vibration of crack faces or joule heating, but traditional flash, lock in and long pulse thermographic methods are not sensitive to these types of defects. Similarly, the benefits of the more established methods are seen in the inspection of composites, with their application in metals much less effective. Therefore, prior knowledge of which method to use in an inspection scenario and how to apply it is essential.

1.4 SOURCES OF UNCERTAINTY

Sources of uncertainty and their relative effects on the measurements that are undertaken will vary between the different types of thermography that have been mentioned. The approach here is to build up from the case of passive thermography for which uncertainty is relatively well defined and largely captured by the uncertainties inherent in the thermal imager used. The uncertainties for the active methods must include all of the inherent uncertainty of the passive measurement plus the uncertainties generated by using active heating and the additional positional and uniformity issues these create as well as the complication that the samples must both be effective absorbers and emitters of radiation in order for a satisfactory measurement to take place. The issue of which measurand is used must also be addressed as well as consideration of how this is usually viewed as a digital intensity level scaled image.

For the case of passive thermographic NDT, the absolute measurement of temperature on the surface of the sample is variable of interest. This can be compared to the temperature recorded from a calibrated thermometry device fixed onto the surface of the sample to give an indication of how accurately well the imager is taking the temperature measurement. In the case of passive NDT, the uncertainties associated with the imaging camera are going to be one of the dominant factors, since the function is to analyse the sample in whatever temperature state it is already in.

When considering the uncertainty budget of a measurement, a typical first step would be to list all the sources of uncertainty that may be present. Once the sources are listed, an assessment can be made of

relative contribution of each source of uncertainty to the uncertainty budget and the uncertainty in the predominant factors quantified.

The uncertainties can be separated according to the part of the equipment or inspection that they correspond to. In thermographic NDT it is logical to split these into:

- Uncertainties inherent in the use of the thermal imager,
- Uncertainties due to the active input of energy
- Uncertainties due to the sample,
- Uncertainties due to the measurement itself.

Using this separation of variables, a list of the potential uncertainties in the measurement can be formulated. Some of these will be common across all of the varieties of thermographic testing and others will be specific to the particular methods. A list of potential sources of uncertainty is provided below

1.4.1 Camera related uncertainties

- Positioning of the camera for repeat measurements.
    - Keeping camera level.
    - Distance to the sample for focus and full field of view.
    - Position of the camera to avoid heat sources (such as the lamps).
    - Angle of camera to sample surface.
- Lens used and therefore effect of the above on lens aberrations.
- Fixed focus vs focussing ring.

- Calibration - the calibration of the reference source, stability of the reference source, stability of the imager, resolution of the imager, drift of the reference source and the residual of the calibration.
- Housing temperature stability.
- Size of source effect.
- Region of interest uniformity.
- Emissivity measurement.
- Emissivity interpretation - applying reference value to actual measurement.
- Ambient temperature– non uniform emissivity of samples means the ambient temperature has an effect.

1.4.2 Active thermography factors

- Lamp uniformity – between different tests and across the sample surface.
    - Distance lamp to sample.
    - Uniformity of heating of sample.
    - Reflection or transmission setup.
    - Repeatability of orientation/positioning of lamps.
- Reflections from other surfaces.
- Power of lamps.
- Lamp filters – the use (or lack of use) of filters to remove unwanted radiation from the signal.
- Specific to flash excitation: with integrated flash lamps (i.e., fixed separation between lamps and distance to sample) – power of flash – any difference will affect the surface temperature in each measurement, duration of flash, IR cooling tail (filters), synchronisation with software.

- Specific to long pulse excitation: timing and duration of pulse, environmental conditions over inspection time, lamp positioning.
- Specific to Lock in excitation: modulation of lamps at desired frequency, software synchronisation, blind frequencies, atmospheric effects (much longer inspection times).

1.4.3 Sample

- Uniform emissivity/reflectivity of sample – many components need to be coated with a matte black paint to remove reflections and ensure uniform emissivity this makes testing more effective but introduces variations if the coating thickness isn't uniform and can prove impossible to apply to parts in situ.
- Size/geometry/curvature of a sample will dictate how effective heating is in the areas of interest.
- Temperature – samples must be at room temperature before testing and allowed to cool back to room temperature between tests.
- Thickness of a sample, defect depth through the sample, the lateral extent and the through thickness air gap caused by the defect are all aspects that affect their detectability. When testing, typically a reference defect is required and there may be errors inherent in the sizing of reference defects that increase in the case of a real defect.
- Angle of the sample to the heat source/camera – forward/back and side to side.
- Consistency in positioning – position and angle may vary.
- Knowledge of material thermal properties, ideally an emissivity and thermal diffusivity for the sample would be known.

1.4.4 Computer/ operator

- Operator bias – often measurements undertaken by expert who applies previous experience to interpretation.
- Computational error of operator or software used to define defects.
- Errors inherent in sizing with machine-based methods.

This list will be used as a basis to assess the current work available in the public domain on the development of uncertainty budgets in thermographic non-destructive testing. It represents a selection of the parameters that can vary in thermographic measurements for non-destructive testing but is unlikely to be exhaustive for all inspection scenarios.

1.5 REFERENCE ARTEFACTS

The large levels of variability in thermographic measurements result in difficulties in knowing whether a part is defect free if no defects are detected or if there are defects present to which the method is not sensitive. Defects can exist at a depth or size that does not result in a significant change in the surface temperature recorded in the sample. As such it is usually necessary to test the detectability of defects in each new material or component by generating artificial defects within a calibration sample.

With thermography, the types of defects that are typically used to assess defect detectability are flat bottomed holes that are inserted in the material on the opposite side to that which is being inspected. This is an approximation to the behaviour that would be seen if a delamination or thinning defect was present in the material. Since the depth of the defect, lateral extent and through thickness extent of any defect have an effect on its detectability, in practice a wide range of different sizes and depths are

required to satisfactorily categorise defects as detectable or not in a specific inspection scenario. The flat bottomed hole side (opposite to the inspection side) of some calibration style defects in different materials and different geometry parts are shown in Figure 1 and Figure 2 respectively. They are designed for maximum detectability or to quantify detectability of different diameter defects at different depths.

If more realistic defects are of interest, these types of flat-bottomed hole defects can be filled with a plug of the same material to reduce the size of the air gap that the thermal wave encounters when propagating through the material. Another form of artificial defect that can be used in materials such as CFRP or GFRP is to insert Teflon tape into the material as it is being laid up which provides an area of difference in the structure. This type of defect is less quantifiable as it will be unclear if an air gap exists and how large it is.

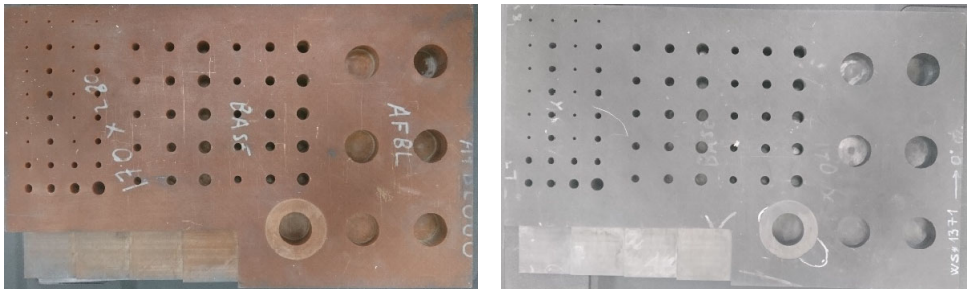

Figure 1 Calibration blocks for thermography with flat bottomed holes of different diameter and depth to assess detectability of defects in glass (l) and carbon fibre (r) samples.

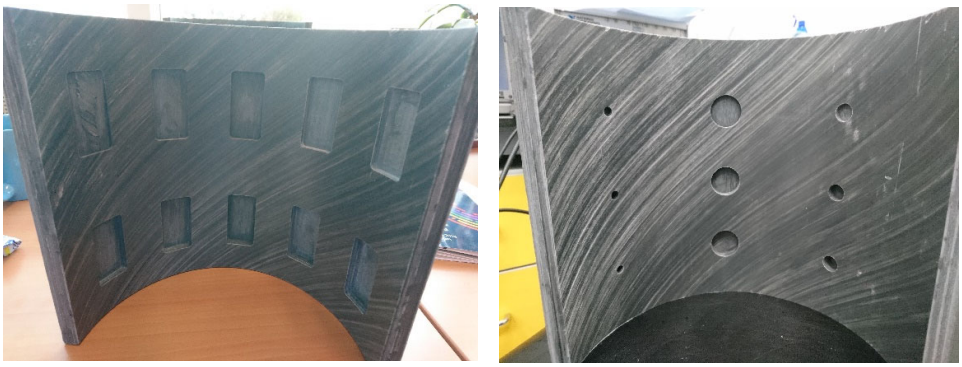

Figure 2 Calibration style defects in a more challenging geometry, for depth determination only (large diameter) (l) and for quantifying smallest detectable defect diameter at deepest depth (r).

Clearly these defects are not representative of some of the more complex defects that will be encountered but provide a controllable analogue of the most detectable defects using thermography.

1.6 REPORT CONTENT AND AIMS

The aim of this report is to collate information regarding the current status of uncertainty determination in thermography, taking what is accepted in passive thermography and relating this to active thermographic NDT. The emphasis is on flash, long pulse, and lock in methods as these are the techniques available at NPL. It is intended to highlight where any gaps might be in the current treatment of uncertainty, discuss the complications in forming uncertainty budgets in these measurements and provide a basis for discussion on the future needs of active thermographic methods.

This is especially pertinent if they are to be used more quantitatively. This then feeds into NDE 4.0 where the inspector is planned to be further removed from the measurement process.

2 PASSIVE THERMOGRAPHY

Passive thermography is the term given to the monitoring of the surface temperature of a sample without actively introducing a source of heat energy. This method is used widely for condition monitoring in various sectors including: condition monitoring of built structures (e.g. civil engineering structures and housing) and condition monitoring of components and machinery. In this context, the camera can either be used to detect the absolute temperature of the sample for close monitoring of the surface temperature or in a more general way. In the absolute temperature application, parts can be monitored looking for small changes from the usual behaviour to quickly highlight any issues. In a more general way, the absolute temperature may not necessarily be important, with just the changes to temperature out of the usual range considered relevant, giving an indication of behaviour outside of tolerance or of a developing defect. A diagrammatic representation of passive thermography is shown in Figure 3 where a thermal imaging camera is used to monitor the temperature of a surface. The presence of an area of difference in the material or a defect will show as a difference in the heat flow at that area.

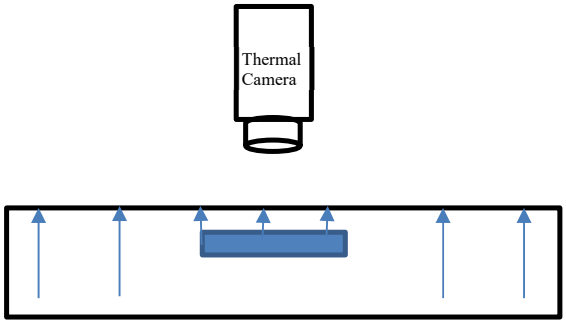

Figure 3 Diagrammatic representation of the way the surface temperature of a part can change due to a defect.

The use of infrared imagers in this context can be used to develop quantitative measurements of temperature. This has typically been a challenging problem to generalise due to the amount of thermal imaging devices on the market and the variety of applications that they are used in.

There are a range of commercially available thermal cameras available that have an array of different properties, they can be sensitive to different infrared wavelengths, have different levels of sensitivity to changes in temperature and different frame rates. The lens can often be changed from a standard range lens to something that works on the micrometre length scale. This can change the uncertainty budget due to the different length scales on which the testing is carried out and therefore the differences in calibration that are required. There has been a considerable body of work carried out in the temperature group at NPL and amongst others to provide assessment of commercially available imagers and their traceability to international temperature standards.

An aspect of this work has shown that the temperature readings of some of the imagers fall outside of the accuracy limits given by the manufacturer and there is considerable variation in the quality of measurements when used outside of the conditions used for calibration. This can cause issues in the direct measurement of temperature but may have less of an impact in a condition monitoring situation where baseline behaviour is compared against current behaviour to assess the difference from a nominally normal level of performance.

A full uncertainty budget has been formulated for a thermal imager in studies by the temperature and humidity group at NPL with extensive testing of thermal imagers to assess their uncertainty [8, 9, 10, 11] when measuring absolute temperature. For the purposes of this report, this work will be referred to here for context in this application, but not explored in detail. Sources of uncertainty highlighted by this work include:

- Calibration - the calibration of the reference source, stability of the reference source, stability of the imager, resolution of the imager, drift of the reference source and the residual of the calibration.
- Housing temperature stability – changes in the housing temperature between calibration and application of the imager can affect measurements.
- Size of source effect – displayed temperature of an object depends on the size of the object.
- Distance effect – the imagers can measure a different temperature at a different distance from the blackbody.
- Region of interest uniformity – the temperature measurements vary across the camera field of view.
- Emissivity measurement.
- Emissivity interpretation - applying reference value to actual measurement.
- Ambient temperature measurement – non uniform emissivity of samples means the ambient temperature has an effect, but this is likely to be small.

These uncertainties are combined into an uncertainty budget for temperature determination of an imager at a particular temperature and for a certain integration time. The expanded uncertainty at k=2 for a 95% confidence interval is 6.8 degrees Celsius. The individual components and their contribution can be seen in Figure 4 from [8].

Source	u	Div.	Sens.	U / °C
Thermocouple				
Tolerance	1.50	1.73	1.00	0.87
Thermometry bridge accuracy	0.20	1.00	1.00	0.20
Stability	0.03	1.00	1.00	0.03
Expanded uncertainty ($k = 2$)				**1.8**
Thermal Imager				
Calibration	0.30	2.20	1.00	0.14
Housing temperature	0.03	1.00	1.00	0.03
Size-of-source	0.18	1.73	1.00	0.10
Distance	0.29	1.73	1.00	0.17
ROI non-uniformity	1.06	1.00	1.04	1.10
Emissivity measurement	0.04	1.00	50.03	2.00
Emissivity interpretation	0.05	1.00	50.03	2.50
Ambient temperature	0.10	1.00	0.01	0.00
Expanded uncertainty ($k = 2$)				**6.8**

Figure 4 Example of an uncertainty budget for the measurement of surface temperature on a sample using a thermal imaging camera, taken from [5].

These uncertainties are quantified by comparing the temperature measured by the thermal imaging camera with the known temperature of a blackbody in a lab-based calibration scenario. Testing has proven that the figures given by equipment manufacturers are not always representative of the true values and have shown that the use of the imager in an in-situ environment with different working distance and source size to that used in calibration can have a considerable effect on the results.

As in all sectors there is a cost-benefit balance to be struck between having an imager that accurately measures temperature and one that is 'good enough' to take the measurement required. It should be noted given the variety of imagers available that they are used for different applications and an imager that is used for the general heat leakage from insulation in a building monitoring scenario will not have to be as accurate at measurement as one use to find defects in a safety critical component. Equally as already stressed many measurements using these devices remain qualitative, and it is only in these more quantitative applications that such rigour needs to be applied.

2.1 PASSIVE THERMOGRAPHY UNCERTAINTY BUDGET WITH A MACRO LENS

The work described above has largely been carried out with thermal imagers with a standoff of 0.5 to 1 metre in the context of imagers used for buildings monitoring and large area testing. Although this is the main application of thermography, which finds favour due to the ability to monitor a large area without the need for contact with the surface, there are other applications that can be considered by using a different lens.

The use of a macro lens allows for thermographic testing on a much smaller scale. This is of interest for testing electronic components either by monitoring the temperature of the part as a current is flowing or by introducing an external source of heat to identify whether there are any areas that behave differently (for example because of solder voids). The use of these lenses has also become more widespread in cases where the defects are expected to be on a smaller scale in general, for example in additively manufactured materials where defects can be micrometre size pores in the material build.

Although many of the uncertainty considerations with these lenses are similar, the scale on which they operate with images of a size of a few centimetres squared is very different from the metre scale monitoring carried out with the more standard lenses. Taking measurements with these imagers can be more challenging as they will have a fixed separation distance from the sample to achieve focus.

The fixed focus distance can vary between imagers. In the case of the lens used in the AEM group at NPL the optimum focal distance is 22mm and in other work a lens is used with a focal distance of 33mm [12, 13], in work by the temperature group the focal distance is 16.5mm [14]. Positioning and maintaining positioning and focus of a lens during a measurement therefore becomes much more important for the validity of the measurement as smaller positional errors in working distance have a greater effect on the results

An uncertainty budget for a measurement of temperature with this lens is again a combination of the uncertainties from the camera and the sample.
Imager:

- Size of source effect.
- Internal reference – temperature within the thermal imager.
- Atmospheric absorption – atmospheric effect on the images.
- Noise – resolution of imager.
- Drift – stability of imager.
- Uniformity – non uniformity across the field of view of the imager.

Sample

- Reference – reference thermometer.
- Emissivity – emissivity of surface or applied coating.
- Reflected radiation – reflected ambient radiation.
- Uniformity – non uniformity of the sample across the surface.

Taking these into account uncertainty budgets were calculated. The NPL based study [14] concluded a value of 640mK (k = 2) expanded uncertainty at 320.67 K. The other investigators [12] obtained values of 1.11 degrees Celsius or 6.59 degrees Celsius depending on whether the sharpness of the thermogram is taken into account, an element that has much more of an effect on the measurement at these length scales. An example of the treatment of uncertainty in these studies is shown in Figure 5 reproduced from [14].

Instrument	Source	u_n/mK	Distribution	Divisor	U_n/mK
		Uncertainty budget			
Sample	Reference PRT	13	N	1	13
	Emissivity	208	N	1	208
	Reflected radiation	199	N	1	199
	Uniformity	60	N	1	60
Imager	Size-of-source effect	113	R	$\sqrt{3}$	65
	Internal reference	50	N	1	50
	Atmospheric absorption	6	N	1	6
	Noise	10	N	1	10
	Drift	30	N	1	30
	Uniformity	90	N	1	90
	Expanded uncertainty 640 mK ($k = 2$)				

Figure 5 Example of an uncertainty budget with a macro lens, reproduced from [14].

Given the issues that these measurements encounter in even the idealised lab-based scenarios on which these studies were carried out, it is certain that any testing made outside of the lab would lead to greater levels of uncertainty.

2.2 PASSIVE THERMOGRAPHY UNCERTAINTIES

Passive thermographic testing where a thermal camera is used to determine the surface temperature of an object is the simplest application of thermography for non-destructive testing. Due to the lack of an external heat pulse, it is also the easiest to define an uncertainty budget for as the parameters for which a budget is required are predominantly dependent on the thermal imager that is used and the sample behaviour.

A considerable amount of work has been carried out in recent years to assess the accuracy claims of thermal camera manufacturers and provide traceability to temperature standards. The variation in imager actual performance against the claimed performance in manufacturers' literature is large. Further complications come from the variety of different applications that these devices are used for. This may mean that the uncertainty in calibration varies from the uncertainty in the actual application of interest by a large margin.

It is accepted that the majority of the testing carried out with these devices is qualitative rather than quantitative and for these applications the accurate measurement of absolute temperature is not as important as the trend of temperature. A balance therefore needs to be made on an application specific basis as to how much the uncertainty is likely to affect the purpose of a measurement. Exact surface temperature measurement with a thermal imager varies if a normal or macro lens is used as the calibration in these two instances is different.

Although concepts from passive thermography (such as camera calibration) can be used to help build uncertainty budgets for active thermography, the number of sources of uncertainty increase. For active thermography the situation is complicated by the dependence on the active input of energy and how this heat flows into and through the sample of interest.

3 FLASH THERMOGRAPHY

Flash thermography is the most accepted method of active thermography used in industry. The use of this method is preferable over others since it provides both qualitative and quantitative data estimates on the position and depth of defects. It should be noted here that although the temperature or thermal diffusivity of the sample is the measurand with respect to the absolute measurement of a quantity in these cases, the aspects that are of interest to the NDT industry are how accurately and reliably the method can detect and size defects as well as how reliable an indication of the depth of the defect that the method allows. So although the measured quantity is one factor, it is the way this is built up into a measurement of a defect that is important.

Flash thermographic systems are produced in two forms and the type of system used will likely have a significant effect on the uncertainty factors that are considered. The most common version of a flash thermographic system involves integrated measurement systems with camera and flash lamps mounted in a flash hood for the concentration of the lamp energy on a certain area. These come with control software to synchronise the flash with the recording. This type of equipment is favoured by industry since it incorporates all the required equipment into one package [15].

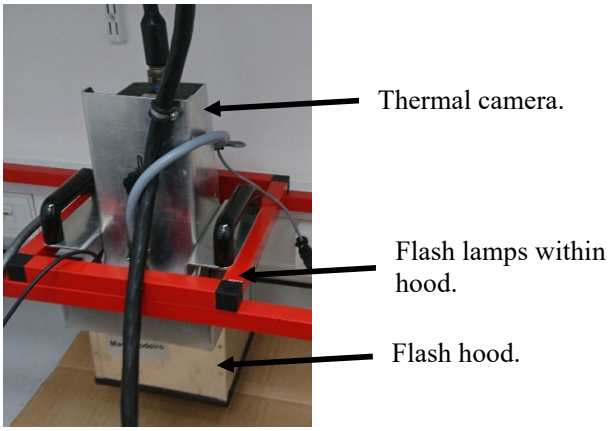

Figure 6 Example of integrated flash thermographic instrument with camera and flash lamps inside a flash hood.

A more flexible form of flash thermographic system is a set of equipment with a separate camera and lamps, allowing a more adaptable setup for testing, better illumination of a larger area and a greater energy input. This type of system tends to be more of a lab based solution [16], but there are companies who supply this type of system commercially [17].

Figure 7 Example of commercially available flash thermographic system from [14] with separate flash lamp and camera.

3.1 FLASH THERMOGRAPHIC TECHNIQUE FOR DEFECT DETECTION OR THICKNESS DETERMINATION

Flash thermography in its basic form is the use of a high-powered flash to introduce a heat impulse into a sample. The energy from the flash penetrates the top surface and propagates through the sample following the physical principles of heat diffusion. The temperature of the top surface is monitored using a thermal imaging camera. When the propagating heat reaches a different area such as a defect or a change in thickness of the material, the heat flow will change in this area. Comparison with any surrounding 'good' area shows up the change as a difference in temperature at the surface. An illustration of this principle is shown in Figure 8.

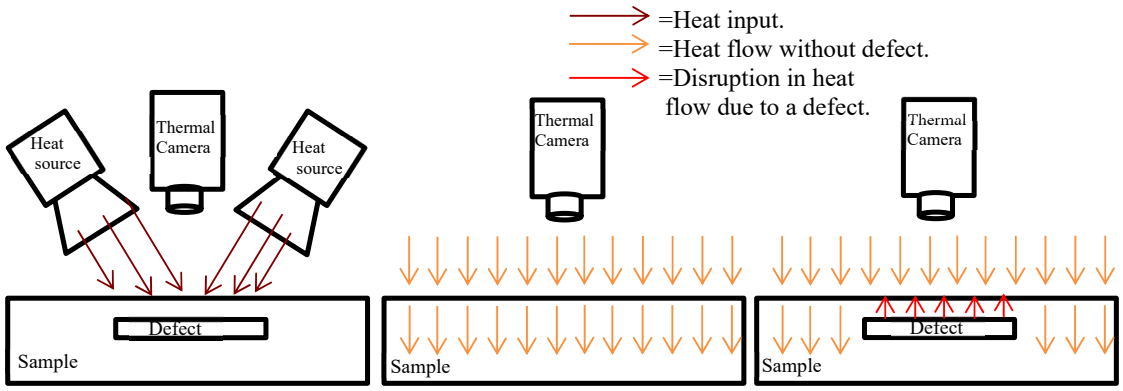

Figure 8 Diagram illustrating the principle behind thermographic NDT, showing from left to right the setup for a thermographic inspection. The heat flow without a defect and disruption in heat flow due to a defect.

The interpretation of flash thermography then splits into two aspects according to whether the information required is qualitative or quantitative. For qualitative measurements, the temperature value at each pixel is combined into a digital intensity map. This can then be used to simply identify areas with different behaviour to the expected in the raw data or undergo processing to show the first or second derivative of the values, which highlight changes.

For a quantitative measurement, the data at each pixel or a group of pixels can be plotted through time. This allows the heat diffusion through the sample with time to be visualised. Synchronised recording with the applied millisecond duration flash allows for knowledge of which frames the flash directly affects and shows at what point the behaviour of the sample in cooling is apparent. In terms of heat diffusion theory, the short duration flash can be treated as an impulse with minimal effect on the rest of the signal, allowing the heating phase to be separated from the cooling phase. The separation of heating and cooling behaviours can also be improved by using a filter to remove the infrared afterglow of the excited lamps from the received signal, improving the signal to noise ratio.

The localised changes in heat diffusion due to a defect can be seen to alter the temperature at the surface and the deviation from the behaviour in a homogeneous part of the sample can be used to estimate the depth of a defect.

In this type of testing the raw data is obtained from the camera at each pixel and thermographic signal reconstruction usually applied which involves the fitting of a high order polynomial to the data in order to reduce noise. The temperature is then plotted against time and displayed in the logarithmic domain. In this representation, the area where there is normal behaviour for a homogeneous material shows a gradient of -0.5. Once the behaviour changes, either from the heat diffusing to the depth of the defect or reaching the back wall of the sample then this gradient changes. Therefore, the change in gradient can be used to estimate the depth of a defect. This is illustrated in Figure 9.

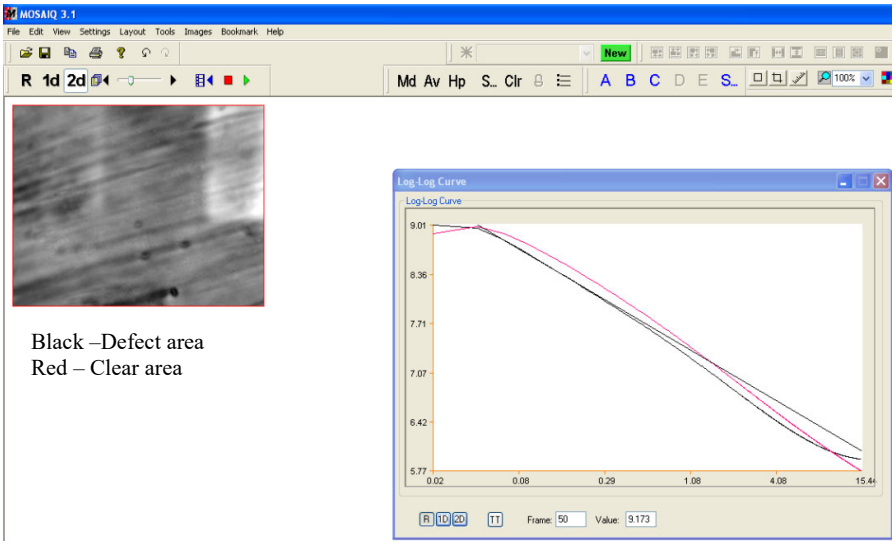

Figure 9 Output from a flash thermographic NDT measurement, with data shown as the 2nd derivative image on the left with a lighter area representing the defect. The change in temperature through time is shown in the graph on the right. The defect free -0.5 gradient straight-line fit is shown along with a line from the clear area in red which is a straight line with a different intercept and a black line showing the behaviour at the defect which deviates from the expected gradient.

Therefore, in Figure 9 a measurand could be the 'digital level of the reconstructed temperature decay profile from the camera' [18] or a property of the material such as thermal diffusivity [19] as calculated using heat diffusion theory. The uncertainties of the measurement of these quantities can then be carried through to assess the lateral extent and depth of a defect.

3.2 QUANTIFYING UNCERTAINTY IN FLASH THERMOGRAPHIC TESTING WITH INTEGRATED MEASUREMENT SYSTEMS

Recent years have seen the beginning of work in the literature to quantify the uncertainty in flash thermographic NDT. This work has built on the efforts to calibrate and establish the uncertainty budget in thermal imagers that have been mentioned in previous sections. Work in these studies has attempted to highlight sources of uncertainty and to consider both lab-based measurements and on-site measurements which require an additional level of operator expert opinion to assess uncertainty contributions. Particular areas of focus include the expert opinion, the effect of repeat tests and multiple samples and the post processing and data analysis that happens to the raw data.

This last aspect of data analysis and how the data is treated to either generate a digital intensity image or to provide quantitative data is particularly pertinent in the move to digitalisation of processes. Knowing the uncertainties that are introduced when obtaining and processing data and when moving to the use of digital recognition and sizing of defects rather than using an experienced inspector will be essential for the digitalisation of the sector.

The experimental systems considered in the scientific literature for assessing uncertainty are typically commercially available systems that are sold as an integrated measurement system. These systems consist of a thermal camera mounted within a flash hood with Xenon flash lamps that can provide 2kJ of energy in a flash through the discharge of a capacitor bank. The system is controlled from a computer with software that synchronises the beginning of recording with the flash. These systems as illustrated in Figure 6, are commercially available.

Consideration of this type of system for uncertainty is partly due to its prevalence in industry but also the fixed nature of the separation between the camera, lamps and sample which reduces the effect of some sources of uncertainty. Some factors in these tests are therefore assumed to be uniform such as camera positioning, the movement of the sample and much of the operator bias that would be inherent in these factors. However, this can be different if the testing is being carried out in an industrial environment where the experience of the operator becomes more important and will certainly have some contribution when the system is not fixed such as when an external flash lamp is used.

Analysis of this testing typically breaks the full system down into several subsystems. Here these are the infrared camera, the flash generator and lamps, the sample of interest and the computer and methods used to process the data.

Having already considered the aspects of uncertainty related to the thermal imager itself, the calibration aspects will not be considered here, but other aspects related to the atmospheric conditions and the distance between the camera and the sample will need to be considered. One of the aspects of this is making sure the measurements are taken at the correct standoff in order to obtain sharp thermal images of the sample. In the case of an integrated system, separation will be fixed but the focus of the camera will likely still be adjustable.

Previous work [18] assessing the uncertainties in a flash thermographic NDT system has identified type A uncertainties related to:

- The intensity reading of the camera.
- Distance between the camera and sample.
- Atmospheric temperature and humidity.
- The temperature of the sample.
- Emissivity of the sample.

Type B uncertainties were also defined as being due to:

- The operator bias.
- Computational error.
- Flash intensity and synchronisation.
- The positioning of the sample.
- The ability to replace the sample in the same position.
- Positioning of the camera.

The work continued to define errors and uncertainty distributions, combine these uncertainties in the subsystems and develop a combined uncertainty for the whole system. However, it also noted that many of these factors are much more difficult to define in the context of testing outside of a lab situation. This means that often an estimate is provided by the operator rather than a quantifiable value. In this analysis, the uncertainties in the flash box subsystem and computation were minimal. The greatest contributions being due to the IR camera itself and the sample.

The measurand in this instance was the digital level of the reconstructed temperature decay profile from the thermal camera. This digital level is the output of the Thermographic Signal Reconstruction TSR technique which involves the fitting of a polynomial to the dataset to reduce the noise in the resulting data. This is often used to improve the images obtained with the technique, making defects easier to identify but the application of the method moves this value away from a genuine temperature value.

In other work by the same authors, different parameters have been considered for uncertainty determination, namely the post processing algorithm, flash power settings and repeat measurements have been considered, with the measurand in this instance chosen to be the thermal diffusivity of the material. The post processing algorithm and the material properties of the materials themselves were the defining factors in the uncertainty budget, although only this subset of uncertainties were

considered. Again, the outcome of this work has concluded that thermography is a technique that requires treatment of testing and uncertainty on a case-by-case basis.

The factors assessed can be compared against the list of possible sources of uncertainty highlighted previously. For these integrated systems the studies appear to cover a broad range of possible uncertainties if all the literature is taken together.

Considering the categories highlighted earlier:

- For this type of equipment due to the fixed positioning of the camera it can be assumed that there are not considerable uncertainties associated with positioning, although unless the sample is fixed there will always be a small element of uncertainty of positioning in between tests.
- The uncertainty in the thermal imager can largely be quantified by calibration as with the passive testing.
- Use of a flash hood fixes the lamp separation and distance to sample through the mounting of equipment within the hood.
- The flash used can vary both in terms of power and duration.
- Testing in these instances has been based on having a sample for which the thermal properties and thickness are well known. Hence there is a known value of thermal diffusivity that is compared against, and the emissivity can be well estimated.
- However, in a real inspection scenario it is likely that a part would not be so well defined and suffer from an element of reflectivity and non-uniform emissivity, with the part likely to need the application of a black paint to normalise the response across a surface.
- The addition of a matte black paint layer in thermographic NDT will introduce other uncertainties into the measurement since it will be difficult to get the thickness of this layer uniform across the sample surface and non-uniformity of this layer will likely show as a surface temperature difference.
- Often the components of interest are of a variable thickness, geometry or curvature which introduces extra sources of uncertainty to be considered.

The assessment in these cases shows how complex the situation can be, with different studies choosing different measurands and a wide range of sources of uncertainty that change with different inspection scenarios. As the UK's national measurement institute, it is part of NPL's role to assess how this type of uncertainty determination is being carried out and to support the development of uncertainty budgets for these measurements. The uncertainty characterisation that has been carried out in studies that have been identified thus far present a good basis, but more work could be done to assess the full range of uncertainties. Work that combined the uncertainty sources in both of the studies above and considered more realistic inspection scenarios and complex parts would provide a more complete view of uncertainty but variability in the method will still require an uncertainty budget estimation for each inspection scenario.

3.3 QUANTIFYING UNCERTAINTY IN FLASH THERMOGRAPHIC TESTING WITH A SEPARATE FLASH LAMP AND CAMERA

Systems that use a separate flash lamp and camera can allow for a more flexible measurement to be made. Removing the requirement that the lamp must be within a flash hood means that several lamps can be used together to generate a higher power flash as long as they can be triggered together. Multiple lamps make it easier to get full coverage of a sample surface and can ensure uniform power input across the sample surface area. When flash lamps are used in this way, they are usually also fitted with a filter to remove undesirable wavelengths of IR radiation that are generated whilst the lamps cool down (after the excitation pulse has been applied). The removal of this energy from the resulting time histories allows for measurements to be taken closer to the occurrence of the excitation flash.

The move from considering the highly controlled system in the case of the integrated measurement system to the more flexible separate systems will introduce a range of new uncertainties based on the coverage and even heating of the sample, the distance between the lamps and the sample and the distance between the camera and the sample. Quantification of these is likely to be challenging since setups will often include a camera on a tripod and lamps mounted on support poles, which by definition are flexible and not at fixed separations from source/sample. The trade-off here is therefore in either sacrificing some of the flexibility of these types of inspections in order to have the equipment mounted on a frame which can allow quantification of separation from the sample and camera or having the lamps free standing on tripods and therefore accepting a larger amount of uncertainty in positioning and energy input.

Therefore, the uncertainty quantification for these separate systems can follow similar principles to the integrated measurement system but will see further additions due to the positioning of all the elements of the system. This may then impact the uncertainties from the sample due to the distribution of the input power across the sample surface.

3.4 DIGITAL INTENSITY LEVEL IMAGE BASED UNCERTAINTY

The studies considered thus far have largely concentrated on the extraction of quantitative temperature or thermal diffusivity data to provide measurements directly. Given the often-qualitative way in which the method is used in industry however, with a digital intensity image generated from the data, it is also considered pertinent to look at the errors and uncertainties that may be present from image analysis. This is particularly relevant with the drive to have much of the interpretation of measurements carried out by artificial intelligence and machine learning in industry in the future.

In this respect the uncertainty can be estimated by assessing the ability to size defects laterally and quantify the depth at which they occur through the use of the captured images. A major complicating factor in attempting to quantify this type of inspection is that there is not a uniform approach to provide temperature scale images across thermal cameras and the settings of all imagers are such that the operator can choose how the image is displayed and the temperature range that the respective colour scale corresponds to.

3.5 IMAGE ANALYSIS FOR THE DETECTION OF DEFECTS

Given that the representation of the data by these systems is often achieved via a digital intensity image as discussed above, it follows that image analysis can be used to quantify the presence and size of defects. In this case there are two main areas of uncertainty. There are the original uncertainties inherent in making the individual temperature measurements that we have been considering thus far. These are the uncertainties related to allowing the system to provide time histories for the value of temperature for each pixel. There are then uncertainties related to how these values are used to identify defect size and shape. These stem from the NDT based desire to quantify defects [20] rather than just the need to identify changes in temperature.

This is usually carried out by an expert operator who can make an assessment not just on the presence and size of the defect but on whether the defect constitutes a danger to the integrity of the part (sentencing of the part) However, with the push to industry 4.0 and the movement of the expert away from the measurement itself, there is a growing body of literature that deals with the digital assessment of this data, which will require an associated assessment of uncertainty. An example of this is the use of intensity levels to identify multiple defects in a single image. This can be misleading when one defect has a high thermal contrast compared to the others in an image, which can happen for defects with different aspect ratios or depths as this will alter the contrast. As such there has been interest into how to achieve this without human interpretation.

The interest in the assessment of defects using more than the expert opinion of the operator has led to work into damage classifiers, pattern recognition, deep learning and confidence maps [21, 22, 23, 24].

These have been carried out for a variety of different situations such as lack of adhesion in thermal barrier coatings, and quantification of impact damage in composites from surface impacts. This is referred to as barely visible impact damage (BVID) and is another area in aerospace which uses the beneficial application of thermography to identify the damage to the composite in different layers. One method in the literature used statistical calculations to assess whether a pixel is part of the undamaged area or a defect and applied this for artificially generated areas of damage and areas of BVID. A more recent study developed this concept and used machine learning to enhance the size and shape determination of real defects with efforts to quantify uncertainty. Another study used segmentation of the images of thermal barrier coating (TBC) adhesion to estimate defect size and shape and attach to these measurements an indication of the uncertainty.

The application of these methods to NDT scenarios both for idealised defects and real impact samples is in its relative infancy due to the complex and unique nature of each inspection and therefore there is a lack of a catalogue of thermographic images from which to draw more statistically significant solutions. It is also noted that it is expensive for highly trained inspectors to classify images of the number and quality required to provide a robust set of training data and to cover the range of defect types that would be needed to cover all circumstances. It is likely that the number of these studies will grow and help to develop the assessment of these defects and their uncertainty in future However, the issue of providing enough data that is expertly assessed will still remain.

3.6 SUMMARY – FLASH THERMOGRAPHY

Flash thermographic systems are the most commonly used equipment for active thermography in the NDT industry. They are often used as integrated measurement systems, but systems that utilise a free-standing lamp and camera are also commercially available. The data analysis of measurements can range from a simple visual representation of the differences seen in a sample to a mathematical estimate of the depth of a defect based on thermal time histories recorded on the sample surface.

Flash thermographic systems are the most appropriate to consider when attempting to apply uncertainty budgets to active thermography since the fixed nature of all-in-one systems reduces some of the uncertainties that are present. It is also a method where heat diffusion theory can be used to provide quantifiable information from each pixel which can be extracted to estimate the depth of a feature.

In general, an uncertainty budget would be required for each different set of equipment and given the variability of thermographic performance in components it would be preferable to be done on a case-by-case basis for each material and component. It is not possible to totally generalise the measurement and provide a meaningful uncertainty budget due to this variation and lack of repeatability.

With an integrated measurement style system where the lamp and cameras are contained within a flash hood the main sources of uncertainty will be the camera and the sample itself. Studies of necessity assume a relatively uniform sample with well-known properties. However, an industrial component or a component that must be tested whilst in situ may not be as well characterised. Often a successful inspection requires a matte black layer to be sprayed on the surface to reduce reflectivity and provide uniform emissivity across the sample surface, but this layer will introduce its own uncertainties to the uncertainty budget.

In the NDT industry it is likely a balance will need to be struck between retaining the benefits of large area imaging and estimates of defects that a thermographic inspection provides and the need to quantify the uncertainties in a measurement.

4 LONG PULSE AND LOCK IN THERMOGRAPHY

Long pulse thermography and lock in thermography involve a much broader heat excitation pulse provided by flood lamps, an example of the setup for this type of testing is shown in Figure 10. In the case of long pulse thermography [25], a single pulse is used to excite the sample and the surface temperature monitored as the sample cools. As the heat diffuses through the sample, different defects can become apparent as the heat flow is disrupted enough to provide an indication of their presence. This technique is less favoured in industry due its more imprecise nature and the lack of depth information from inspections. However, in certain situations and materials it can have benefits as compared to flash thermography. Most notable of these advantages is the low cost of such an inspection since the heating pulse can be provided by non-specialist equipment such as off-the-shelf flood lamps for home security or heat guns.

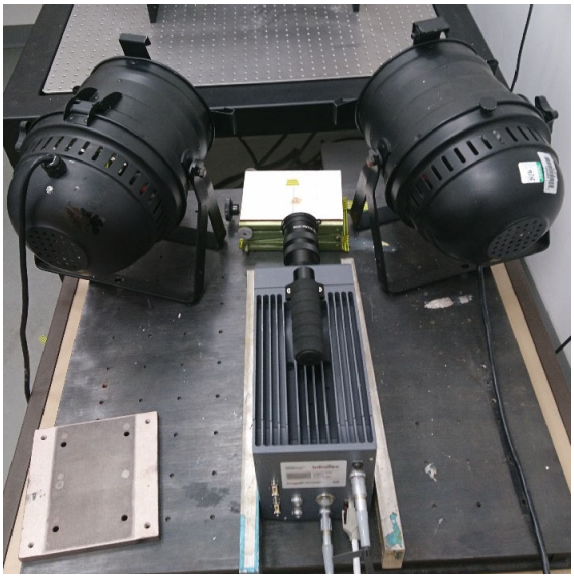

Figure 10 Typical setup for reflection-based thermography using flood lamps - common for both long pulse and lock in applications.

Lock in thermography [26, 27] can again use low-cost excitation methods such as flood lamps but the inspection itself is more complex and requires more computation power, as the lamps are sinusoidally activated to provide a periodic heating pulse to the sample. This is synchronised with the data capture such that the phase of the input energy can be compared with the phase of the measurement of the temperature at the surface. Using this method allows for a depth estimation of defects and can be used on different materials compared to flash thermography, but due to requiring a lower frequency to penetrate further into a material the inspection times can become prohibitively long. The defect depth information from this method is also challenging to extract since there is a complex relationship between the lateral size of the defect and the depth of the defect due to the longer timescales. These longer timescales require a more rigorous applications of heat diffusion theory with less simplifying assumptions possible.

5 LONG PULSE THERMOGRAPHY

Long pulse thermography can be achieved in various ways. The least controlled of which is simply to apply heat from a heat gun to thermally excite the sample and to monitor the cooling of the sample surface. This is effective for some materials such as composites with large defects where the material has a slow response to heating. However, this application is purely qualitative, and is typically used to scan a sample in order to locate defects in a screening manner.

A more controlled application is to use a flood lamp to provide the excitation. In this application, the flood lamp is activated for a period of a few seconds (usually 10) and then switched off. The surface temperature is then monitored as it cools. As the heat diffuses through the sample, defects of different size and depth can become apparent as illustrated in Figure 11. This means a longer time period has to be monitored in this technique of the order of minutes (as opposed to flash thermography where the full response to the heating from defects is usually apparent after 30 seconds). This is due to the differences in the duration and form of the excitation signal.

The use of long pulse excitation makes it much more difficult to identify small defects since the broad excitation means that the excitation and the response of the sample to the heating cannot be separated from one another as effectively as with flash thermography. This difficulty results in the use of these methods as qualitative methods, where the image of the defect is used to estimate the extent of the damage. Some improvement of the quality of the measurement can again be achieved by using shutters to cut off the flood lamps from the sample after the excitation signal has been administered. This can limit the amount of infrared radiation that reaches the sample after the intended heat pulse is finished, such that there is a more defined end to the heating phase.

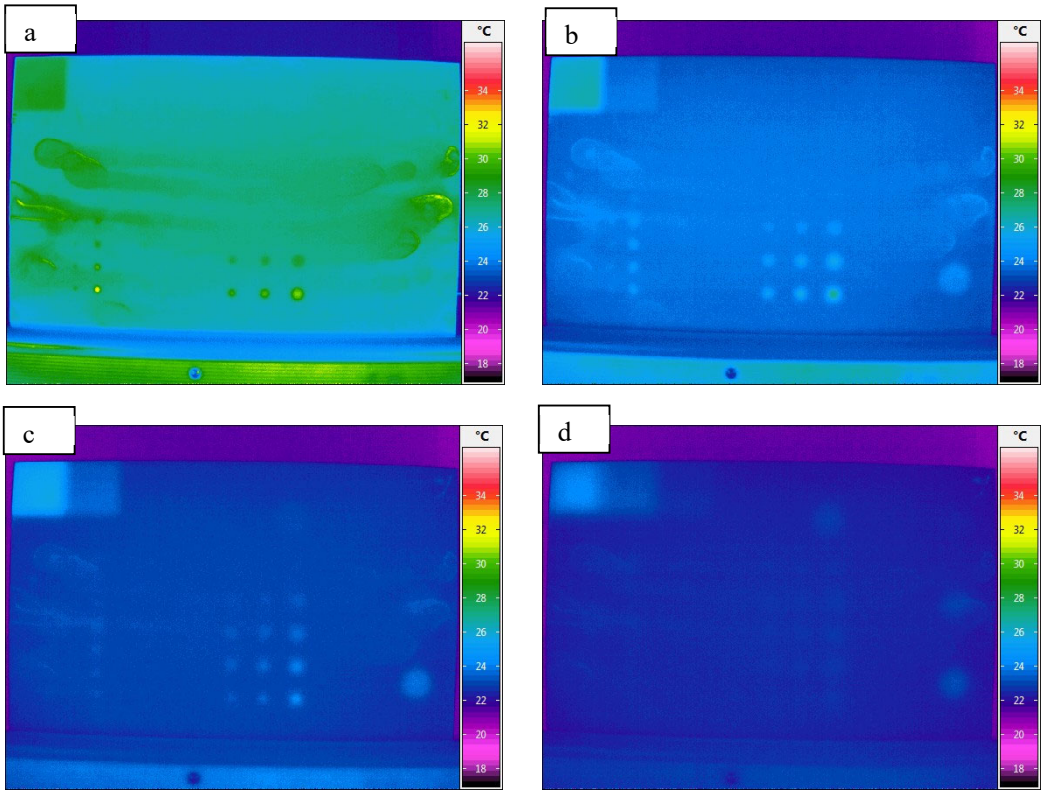

Figure 11 Examples of images from a thermal camera of a GFRP sample with artificial flat-bottomed defects as it cools through time (a-d) from an initial long pulse excitation. Deeper defects with different aspect ratios can appear later in time but the response is blurred by the increase in lateral heat diffusion and therefore there is a greater uncertainty in their size.

Although a useful tool for locating defects in some samples, selecting a reliable measurand and therefore an uncertainty budget for this type of measurement is complicated since quantitative measurement is not in general possible. Given that the method is used as a more flexible technique for applying excitation and recording responses, there are also a wider range of uncertainties to apply to the situation than in the case of a flash thermography inspection with an integrated system.

Some uncertainties in a long pulse inspection will be in common with the uncertainties in the flash thermographic inspection case with separate lamps and camera, but the measurand will be less quantifiable.

The main sources of uncertainty will be:

- The thermal imager calibration (with the uncertainties inherent in this as seen in the passive and flash thermography cases)
- Uniformity of the heating of the sample – positioning of lamps, for each test and repeat measurement. Flood lamps will emit a more diffuse light than flash lamps and will therefore be less directable so will produce a less consistent excitation. The uncertainty in the provision of a uniform excitation signal across the surface of the sample will therefore be higher than in the flash case.
- Positioning of the camera relative to the sample and the excitation source – uncertainties in positioning for imaging and obtaining a focused image and correct coverage, this includes camera positioning in the horizontal and vertical directions and the angle of incidence of the imager at the sample.
- The timing and duration of the pulse – Uncertainties in the timing and duration of the pulse will be present since this is achieved via operation of the flood lamp which will not be instantaneous as in the case of the flash system.
- Knowledge of thermal diffusivity of the sample – real components or components in situ are likely to have a greater uncertainty in thermal diffusivity due to differences from ideal lab conditions.
- Surface finish – reflectivity and emissivity of the component – this will have considerable input to the uncertainty since it determines how much energy can be input into the sample and how much is emitted to be recorded by the imager.
- Sharpness of defects and transition from ‘good’ material to defective area will be less defined due to different heat diffusion behaviour through the sample, this will be compounded with depth through the sample. The effect of this will be a greater uncertainty in the sizing of detected defects.

Given the more approximate nature of long pulse thermography with flood lamps or a heat gun, it may be that this suggestion of the common and additional sources of uncertainty compared to the flash method are the limit of what can currently be achieved in uncertainty quantification for this method.

Long pulse thermography will experience many of the same issues as mentioned in the flash thermographic section when attempting to quantify the defect size using digital methods, with associated uncertainties. However, due to the more complex heat diffusion behaviour with the broad pulse excitation of the sample and greater effect of heat diffusion, the indications from defects will be more blurred, an effect which will increase with depth as lateral heat diffusion plays more of a role. This will result in less defined edges of the defects in detection and therefore a greater uncertainty in the ability of the algorithms used to define the size and shape of a defect.

5.1.1 Summary long pulse thermography

Long pulse thermography is a method that is unsuited to the determination of uncertainties both in its nature and the way that it is used in industry. Parallels can be drawn from the flash thermographic NDT area to make assumptions as to the largest sources of uncertainty. However, since the method is in general used to locate defects and give an estimate of size and depth on a length scale basis rather than an exact measurement basis, the formulation of a reliable uncertainty budget for this method will be challenging to achieve. This is acceptable in this variety of testing but if this method moves further into the quantitative measurement domain, then this concept should be revisited.

It should be noted that the assessment of methods here is being carried out on a generic basis, it may well prove that detailed assessment on a specific inspection scenario would allow for quantification of uncertainties in the process to a greater degree. However, as before, typically every component and inspection scenario will be different and therefore any uncertainty budget would of necessity need to be bespoke to the situation making a generalised uncertainty budget for the method irrelevant.

6 LOCK IN THERMOGRAPHY

Lock in thermography is a variation of thermography that uses the same excitation concepts as long pulse thermography but with modulated, periodic heating. It involves inputting a periodic heating pulse to a sample and capturing the response to the heating. Whereas in the other methods considered, the amplitude of response is the variable that allows an image to be constructed, in lock in thermography both the amplitude and the phase can be considered.

When the excitation pulse is absorbed at the sample surface it is phase shifted, this wave is then reflected from areas of difference within the material, interacting with the input wave and setting up an interference pattern. The phase shift between the input wave and the reflected wave can be used to identify defects. The benefit of such a method is that it can mitigate some of the issues related to surface finish and emissivity that can obscure defects when only looking at the amplitude of the pixel response through time. It can also be used to give an estimation of defect depth.

The success of an inspection using lock in thermography depends on the properties of the material and the depth of the defects or thickness of the sample. Using a different frequency to modulate the lamps and excite the sample obtains an image of defects at a different depth through the sample.

As the frequency is reduced, defects can be found at a deeper depth in the material. Although this makes it a more versatile method for locating defects, it means that an appropriate frequency is required to probe the depth of interest in the material and that several frequencies may be required in order to detect all of the defects present if they occur at different depths. The requirement to use different frequencies arises because of the phenomenon known as the blind frequency [28]. This occurs in the phase images of the sample where below the blind frequency a given defect shows as a white spot in a grayscale image and at other frequencies shows as black. In the frequency range between these two, the defect merges with its surroundings in the grayscale image and becomes difficult to detect. This is purely a 3D heat flow effect which complicates the analysis of these problems.

Quantification of defect depth is also nontrivial and can be challenging to achieve [29] this is in part due to the complex 3D heat diffusion behaviour that is seen. This behaviour means a defect indication is dependent on its lateral extent as well as the depth in the material that it is found, with difficulty in separating the two effects on the signals.

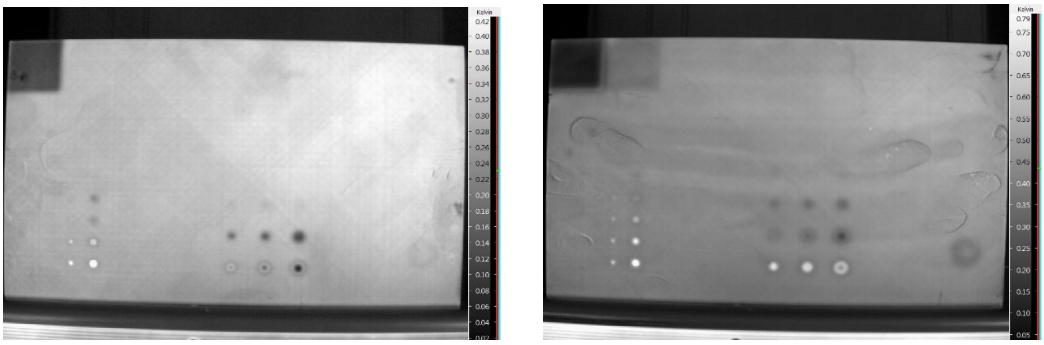

Figure 12 Example of different depth and size artificial flat-bottomed holes that are detected at different frequencies (left) 0.16Hz and (right) 0.08Hz in a GFRP sample.

Typically, the method can locate defects deeper within the structure of a material such as a composite panel, but there is a corresponding increase in inspection time particularly with the deeper defects. This is not only due to the relationship between time and frequency, but the inspection is also extended by the need to take several cycles in order to establish the cyclical heating in the sample. Heat cycling can be achieved with a minimum of 1.5 to 2 cycles, but it often requires more than this minimum in order to obtain a satisfactory result. The slow speed of inspection would result in greater uncertainties due to the greater variation of conditions across a longer timescale. It also means that often there is a different NDT method that is more appropriate for the location of these defects in industry, hence its relatively slow uptake outside of a lab environment.

Lock in thermography can be performed with the flood lamps discussed previously for long pulse heating and also with the use of modulated laser pulses [30]. Inspections with lock in thermography will have many uncertainties in common with the previously considered methods, including:

- Thermal imager-based uncertainties as discussed in the same manner as passive testing.
- Sample reflectivity, absorptivity and emissivity-based uncertainties. Although the surface effects of the sample can be mitigated by considering the calculated phase difference signals, there will still be reflectivity-based issues related to achieving adequate input of energy.
- Relative positioning and repeatability of positioning of camera, lamp and sample relative to each other and the ability to provide uniform illumination of a sample.
- Atmospheric effects - Some of the inspections are required to take place over a long timescale in order to setup the heating cycles and to reach the depth of interest. Therefore, it is anticipated that changes in atmospheric conditions may have a greater effect on the measurements and uncertainties in them than in the much quicker measurements using flash and long pulse thermography.

In addition to these factors that are common to the other thermographic techniques considered, there will be additional uncertainties related to:

- The ability of the software to achieve modulation at the required frequency.
- The ability of the lamps to match this frequency including how high or low amplitude lamps can be operated at. (If a laser is to be used there will be a corresponding uncertainty in the laser timing but is likely to be a much smaller effect.)
- The ability of the software to synchronise the data recording with the input signal.
- Digital representation of the amplitude and phase on an image or the raw data.
- The phenomena of ‘blind frequencies’ as mentioned where phase images for some defects disappear may increase the number of frequencies that are required to test the whole of the thickness for defects. Each of these inspections will be different, not just a repeat. A certain frequency may decrease the uncertainty in sizing of a defect but increase the uncertainty in the detection of a defect at a different depth.

6.1 MOVING TOWARDS QUANTIFICATION OF UNCERTAINTIES

Quantification of uncertainties in lock in thermography as with long pulse thermography is a challenging field. Fixing the separation between the lamps, sample and camera would allow distance and angle-based uncertainties to be quantified. In depth consideration of the software and excitation signals used to generate the sinusoidal energy input and interpret this could be used to determine the uncertainty in this process, but often the software operate on a ‘black box’ basis where minimal documentation is provided to explain the processes that happen behind the user interface in the

software. A detailed assessment of the environmental conditions and the effect of variability in these conditions on the measurements would allow uncertainties due to this aspect to be estimated but this is likely to become less possible and relevant when more complex inspection scenarios are of interest. The samples used would have to be characterised in each inspection instance to determine uncertainty in the reflectivity and emissivity and in any layer of paint that is applied.

This list of additional requirements for identifying uncertainty contribution in a lock in thermography inspection will prove prohibitive for most inspection scenarios due to the number of variables that need to be considered and their inter dependency.

6.2 SUMMARY LOCK IN THERMOGRAPHY

Lock in thermography can be a useful tool to detect defects in materials and give an estimate of defect depth. However, the uncertainty in a defect's size and depth measurement will increase if it is located deeper in the sample. This is due to the heat diffusion behaviour that occurs as the energy propagates into the sample. Obtaining an uncertainty budget for lock in thermography would be a complex process dependent on many factors. With this method there are many sources of uncertainty that would all need to be assessed.

Firstly, the collection of temperature data as in the way of the other methods would need to be considered for contributions to the uncertainty budget. Next the uncertainties related to the periodic excitation of the sample and the synchronisation of this with data capture would need to be considered along with the factors in common with the other methods related to the samples of interest such as the measurement of the emissivity and the effect of a paint layer if one is applied. Finally, the assessment of the uncertainties related to the ability to quantify defect size and depth would need to be calculated since this method is usually used to find defects using the digital intensity levels of an image as discussed earlier. Given the number of variables that need to be quantified along with their uncertainties in these inspections it is likely that the situation would be similar to that of the flash thermography case where studies are only able to consider a subset of the factors in each assessment and therefore would largely remain qualitative.

7 CONCLUSIONS

The development of uncertainty budgets for thermographic NDT measurements is challenging. The treatment of uncertainty in thermographic NDT measurements is in its relative infancy. This is due to an historic lack of demand for such studies of uncertainty due in part to the acceptance of other criteria such as probability of detection of a defect as satisfactory to determine whether the method is 'good enough' for use in industry. It is also in part due to the acceptance that thermography itself is best used as a qualitative tool which gives the indication of the presence of defects in a material. However, like any effective method of NDT, as it is used in more situations in industry, more is asked of it. This has led to its use for more quantitative measurements and therefore requires an understanding of uncertainty when considering these methods.

Despite a move towards obtaining more quantitative measurements the majority of testing using thermography remains qualitative. The method is seen in much of the NDT industry as a screening technique, used to identify the presence of defects through the visual difference between the infrared imaging of a damaged and defect free area. The limiting of the technique in general stems from an acceptance in industry that obtaining reliable repeatable measurements is difficult due to the variability of measurements. This variability can be attributed to material properties, sample geometry, surface finish, positioning of sample, heat input, and camera.

The area of passive thermography, that of monitoring a sample surface to track its temperature without introducing an external source of heat has enjoyed a large amount of study in recent years. This has led to full uncertainty budgets being formed for these measurements and an assessment of calibration for the temperature read by these imagers compared to known calibrated thermometers. These studies

have shown that the performance of these imagers can vary from the manufacturers' claims and emphasises the need to consider the measurement that is taking place and how much it differs from the conditions that these imagers are calibrated in. The maturity of uncertainty determination in this part of the sector is good and could be applied to instances where the equipment is used in condition monitoring applications.

For NDT purposes, thermography is usually of an active nature where there is an input of energy to the sample of interest and the response of the sample to this input energy is monitored through time. This behaviour follows the principles of heat diffusion and often the practical measurements are supported by heat diffusion theory and modelling. The most common of these applications use either a flash to input energy into a sample or flood lamps. In the case of flash lamps being used to input the energy, the energy is input on the order of milliseconds. From a theoretical point of view this can be considered as an impulse and the majority of the cooling behaviour can be attributed to heat flow through the sample. The nature of this means that the temperature can be monitored through time and compared against a precise temperature measurement to quantify uncertainty. The decay of the temperature through time can be extracted to give a measurement.

The form of many of these flash systems as integrated measurement systems including the lamps and the camera allows for the reliable quantifications of uncertainties related to the positioning of the lamps, samples, and camera. As such, studies have been carried out to identify the main sources of uncertainty in these systems and this has progressed into assessing the uncertainties in defining the dimensions and depth of defects with a view to how machine learning and AI could be used to quantify the defects that are found.

The other large sector of thermographic NDT features the use of flood lamps to provide a long pulse (10 second) excitation or lock in thermography where a periodic heating pulse is applied. These methods have seen less attention in attempts to provide uncertainty budgets due to the lack of quantifiable aspects in long pulse thermography and the complex heat diffusion behaviour that occurs with lock in thermography which make it challenging to provide definitive measurements.

An assessment of the sources of uncertainty in these methods has been carried out building from the parameters that are in common with both passive and flash thermography. Concepts can be used from these methods to assume the effect of uncertainties in long pulse and lock in methods, but these also have additional sources of uncertainty which are difficult to quantify. These include the synchronisation of lamp operation and data recording, the uniformity of heat application across a surface and the additional effects of the ambient conditions that can have an effect due to the longer experiment duration. This difficulty is compounded by the lack of sharpness in defect indications as they are located further through the thickness of the sample, which affects the ability to determine the dimensions of defects. The number of variables and the uncertainties related to these variables mean that uncertainty budgets would need to be calculated for each inspection scenario and sample individually. The interdependency of these parameters would likely mean that multiple different test scenarios would be required to quantify the sources of uncertainty in these methods.

The qualitative nature of many thermographic NDT measurements as discussed makes an uncertainty budget challenging to develop and in many cases unnecessary to apply but in the more quantitative measurements budgets can be developed and applied but typically require consideration of each different inspection scenario and sample.

7.1 NEXT STEPS

Further input is required from industry as to the need and desire to apply uncertainty budgets in the thermographic NDT inspection scenarios considered in this work. Although the uncertainty in passive and flash thermographic methods are largely quantified, additional work could be done to collate the uncertainty sources from various inspection scenarios and studies to determine uncertainty and attempt to generalise the budgets for the methods as much as possible.

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