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A practical guide to infra-red thermography for building surveys

J M Hart

Building Research Establishment
Garston
Watford
WD2 7JR

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SUMMARY

This BRE Report gives a guide to the use of infra-red thermography as a means to investigate the thermal properties and hidden constructional details of building envelopes.

An introduction is given to infra-red thermography, the operation of the camera and the difference between photography and electronic thermography.

The guide describes the aims and requirements for carrying out an infra-red survey and discusses thermal analysis and application of the results. Also included is a section on sources of interference which can occur during thermography and may lead to misinterpretation of the results.

Examples are shown of the qualitative and quantitative analysis of infra-red data used to study insulation defects, air infiltration, the heat loss from windows and many other qualitative building applications. For lightweight responsive components such as windows, U-values have been calculated from quantified thermograms to enable comparisons to be made between forms of window insulation. In heavyweight non-responsive components, the technique has been extended to combine the visual thermal image with that of U-value measurement using a heat flux meter.

In the appendices, an introduction is given to the physics of thermal radiation and the derivation of emissivity and its importance in the infra-red technique. Also included is the derivation of the basic analysis formulae and their practical application to the AGEMA infra-red thermal imaging camera.

1 INTRODUCTION

This report gives guidance on the use of infra-red thermography in applications in the construction industry. It provides an outline of both theory and practical details of surveys and shows how these can be applied in a number of situations. The techniques have general application outside the building industry, in situations where differences in the surface temperature of objects reveals information about the underlying structures of services or materials. This is particularly useful in inaccessible or hazardous locations, for example high level ducting.

Infra-red thermography can be simply defined as 'seeing heat'. Infra-red instruments measure radiation from an object surface and display the result as visible light on a TV type display. The product is called a thermogram. The ability to rapidly visualise surface temperature gives thermography a wide scope of application, particularly in the field of non-destructive testing. In the building industry, thermography may be applied to many facets of building performance and performance of components and services. These include:

- Insulation defect detection
- Air leakage detection
- Heat loss through windows
- Dampness detection
- Detection of 'hidden detail' - eg subsurface pipes, flues, ducts, wall ties, etc.
- Examination of heating systems, - eg efficiency, damage to insulation, blocked pipes, heat distribution, failed control equipment (steam traps), etc.

- Preventative maintenance
- Electrical defect detection
- Leakage from earth embankment dams.

Guidance is given on how to carry out surveys (see Section 5) and a number of different applications are detailed (see Section 8).

An infra-red survey of a building or its components can take several forms depending mainly on the survey aims and the nature of the structure. Increasing the complexity of any survey means increasing cost, therefore the end product and any potential savings must be considered at the outset so that the survey may be carried out accordingly.

There are two approaches for carrying out a thermographic inspection, the qualitative and the quantitative approaches. The qualitative approach is the most straighforward. It may be used, for example, to find hidden detail, blocked pipes or missing insulation by observation without the need for measurement detail. Very often images from this type of survey are interpreted by a skilled operator on-site with 'hard-copy' thermograms presented as confirmation of the findings.

The quantitative approach, being a more detailed and stringent survey tends to be more time consuming and costly, but as a measurement technique it is the best approach. For example the determination of insulation faults where a straight comparison would be misleading (ie where areas under investigation have differing surface emissivity or where surfaces are subject to different thermal environments).

In general, the results from a quantitative survey are not analysed on-site. The thermal images are recorded onto video tape along with an audio commentary and all the necessary parameters for off-line analysis. The information is then replayed back in the office for analysis by computer. A full report may then be produced giving for example, surface temperatures, area analysis and statistical information, together with 'hard-copy' thermograms in black and white or colour.

The apparent simplicity of the infra-red technique can lead to serious misinterpretation of the results if certain precautions and procedures are not fully understood and adhered to before and during the survey. These include:

- The environmental thermal conditions both inside and outside the building prior to and during the survey, (see Section 6);

- Allowing for any unusual thermal influences, eg shading, hot or cold reflections, differing surfaces finishes, etc. (see Section 7);

- The measurement of all the parameters necessary for thermal analysis, ie. emissivity, air temperature, object distance, camera settings, etc (see Section 4).

2 THERMOGRAPHIC AIMS AND MOTIVATIONS

The main reasons for a thermographic survey are: improvement of design, assessment of workmanship and investigation or avoidance of failures.

In the domestic sector, the main aim is to provide a relatively fast and cheap survey to identify areas of great energy loss which could be readily remedied or improved by the private or public sector owner. Thermography may typically be used, for example, to verify that insulation has been properly installed to inspect workmanship and identify the benefits of improved energy efficiency in housing rehabilitation projects.

Additionally within the domestic sector there is an increasing use of computer-based energy auditing packages to study the thermal performance of existing building stock and to produce energy efficient designs for new build. In this field the results from quantitative thermographic surveys on completed houses may be used in model validation and as a basis by which thermal improvements may be compared.

Industrial applications tend to be of a more diverse nature ranging from simple structural surveys, through to energy auditing and services troubleshooting. However, the general requirements for a successful thermographic inspection remain the same and the main differences occur in the size of the survey and in the application of results.

The three main areas of thermographic inspection are:

2.1 Design

Many modern buildings, and existing buildings which have been the subject of thermal upgrading, have been designed to optimise their use of energy. By inspecting these buildings using thermography the effectiveness and 'buildability' of energy conservation measures can be assessed. Using this approach, energy wasting design features can be identified and the effect of problematic build features visualised. These thermographic results may then be used to improve future building thermal design.

2.2 Workmanship

Poor workmanship may make well-designed buildings energy inefficient. In addition, retrofit energy conservation work (eg cavity wall insulation) must be carried out correctly for maximum fuel saving to be realised. The use of thermography as a means of quality control may be used for the installation of retrofit insulation as well as in new constructions. In many insulation techniques it is very difficult for the installer to know how well the insulation is being installed, for example in the common use of injected cavity fill. The installer cannot always be certain of the quality of work. Thermography will provide both the installer and the owner with visual proof that the insulation has been properly and effectively completed.

2.3 Failure

Even if the building has been designed properly and all components installed correctly, the building may still become energy inefficient because of component failure. Thermal insulation may deteriorate, electrical fittings may become defective and overheat, and on large site heating systems steam traps may corrode and remain open, pipe insulation may be old and damaged and heat exchangers become less efficient. Any of these conditions will result in unnecessary waste of energy and all may be identified using thermography. In some cases, complete component failure may be avoided by the early detection of a malfunction.

3 THERMOGRAPHY AND THE INFRA-RED CAMERA

3.1 Thermography not Photography

It is important at this point to distinguish between infra-red (thermal) photography and electronic thermography.

The radiation we call visible light, forms a very small part of the electromagnetic spectrum, see Figure 1. In addition to the visible radiation, there is also a broad expanse of 'invisible' radiation at either end of the visible band. Beyond violet lies a region called ultra-violet, then X-rays and gamma rays. These regions are regarded as short wavelength radiation and all will expose photographic film.

At the other end of the spectrum, at wavelengths longer than red, lies infra-red, and beyond that, micro-waves and radio waves. These regions are regarded as long wavelength radiation and very little can be recorded directly onto photographic film. Normal photographic emulsions are sensitive to the visible wavelengths up to about 0.65 μm. However, it is possible to extend spectral sensitivity into the near infra-red by adding special sensitizers to the film during manufacture. Even so, most infra-red films have little sensitivity beyond 0.9 μm with a fundamental limit being reached at 1.3 μm where the energy of a photon is insufficient to create a latent image. Furthermore, serious photographic problems would arise as thermal sensitivity is increased because even warmth from the camera body and the surroundings would fog the film.

So if we are to 'see heat' an alternative form of imaging must be used and this is known as infra-red thermography.

3.2 Thermal radiation

The infra-red or thermal wavelength region extends over the range 0.7 to 1000 μm and is sometimes subdivided into a near region (NIR 0.7 to 3.0 μm),an intermediate region (MIR 3.0 to 6.0 μm), a far region (FIR 6.0 to 15.0 μm) and an extreme region (15.0 to 1000 μm). At all temperatures above absolute zero every object emits energy from its surface in the form of a spectrum of differing wavelengths and intensities. The particular spectrum emitted by a surface depends upon its absolute temperature and its emissivity. As the temperature increases, the amount of energy emitted at each wavelength increases. In addition, the wavelength at which peak radiation occurs becomes shorter.

In general, there are two regions over which infra-red thermal imaging cameras can be sensitive, they are the intermediate (MIR) and the far (FIR); historically most civilian measurement equipment have used the MIR region and military thermal imagers have used the FIR region. More recently the FIR region has become more popular as infra-red detector technology improves.

The detection of this invisible thermal energy to form a visible thermal image and its subsequent interpretation depends broadly upon the following four points:

(a) The thermal characteristics of an object surface. (See Appendix 1);

(b) The response characteristics of the infra-red camera. (See Appendix 2 and Section 3.3);

(c) The influence of microclimate on the object and counter reflecting surfaces. (See Sections 6 and 7);

(d) The thermal attenuation of the atmosphere between the camera and the object. (See Appendix 2).

3.3 The infra-red camera

Thermography is defined as a technique for portraying an object using the thermal energy radiating from the surface of that object. The basic task of the infra-red camera is to detect this radiation, convert it into an electrical signal and display the result as a thermal image on a television screen. The system is similar in conception to a portable video system, see Figure 2, the difference being the wavelength of the energy gathered to form the image. A normal video image is produced from reflected radiation over the visible wavelength range (0.4 to 0.7 µm). The thermal image, however, is a visible reproduction of the radiation received from an object surface in the wavelength range 3.0 to 5.6 µm. Because the infra-red camera is sensitive to radiation over this wavelength range, the camera optics are very different to that found in a modern video camera.

In order to be able to measure the total energy flux E, radiating from the surface of an object, infra-red cameras working in the 3.0 to 5.6 µm wavelength band use indium antimonide as the radiation detector. To increase its sensitivity and stability the detector is maintained at a low temperature, -196°C, by liquid nitrogen. At this temperature it is sensitive to the wavelength range 1.5 to 5.6 µm. However, like all cameras a front object lens is necessary to focus the infra-red radiation to form an image. As glass is partly opaque over this wavelength range, (see Appendix 1.4 and Section 8.4) silicon is used for the object lens. Thus the optics combine to give the short wavelength infra-red camera an operating range of 3.0 to 5.6 μm, well placed to take advantage of the atmospheric 'window' over that wavelength range see Figure 3.

To produce a thermal image of an object as a whole, using only one detector, requires the individual energy fluxes emitted by a large number of partial elements to be measured and electronically combined. In order to do this most infra-red cameras are equipped with an optical-mechanical scanning system. A scanning system may be comprised of prisms or mirrors or a combination of both. In the case of two prisms, one rotates slowly in the vertical plane the other much faster in the horizontal plane. A virtual image formed by the object lens on the first (vertical) prism is scanned by the horizontal prism to form a line image, then by interlacing the two prisms, the line is progressively stepped down to cover the entire object surface. Following the scanner mechanism, the radiation passes through collimating lenses and a rotary chopper before reaching the infra-red detector. The whole process is very fast resulting in as many as 25 complete image frames per second.

In common with many other cameras the front object lens of the infra-red camera is interchangeable so as to provide different fields of view, see Figure 4 (a and b); also a selectable aperture control enables the camera's sensitivity range to be matched to the intensity of the object radiation. In addition, the operating wavelength range of the camera can be reduced by fitting spectral filters to the internal filter 'cassette', when required, the appropriate filter can be rotated into the internal radiation path thus modifying the cameras spectral response.

The radiation flux received by the infra-red detector generates an electrical voltage signal, the amplitude of which is proportional to the point by point temperature variation across the surface of the object scanned by the camera. The output voltage signal is then amplified by a video pre-amplifier before being passed, via an interconnecting cable, to the display monitor. Where, after further signal processing, a thermal image in visible light is produced on the screen of a cathode ray tube.

3.4 The thermal picture

In its basic form the thermal image appears on a monochrome monitor as a 'real-time' continuous grey tone picture. The intensity of the light on the screen represents the magnitude of the emitted radiation received, by the camera, from the object surface. On a normalised display, the grey tone shading shows the magnitude of this received radiation such that black areas of the image are relatively colder than white areas.

The display monitor also shows the system sensitivity range and a scale of isotherm units which enable the user to estimate relative temperature differences, see Figure 5.

A permanent record of the thermal image displayed on the monitor screen can be produced by photographing the screen using a conventional camera and film. The resulting hard copy is called a thermogram.

The thermogram shown in Figure 6, is a qualitative image of the internal face of a cavity filled wall, but some of the insulation is omitted. From the image alone, it is only possible to say that the black area is relatively colder than the white by an amount governed by the sensitivity scale used, (in this case; scale 5). It should be noted, however, that even this statement assumes a uniformly high surface emissivity and no unaccounted thermal influences on the surface.

3.5 Image recording

When analysis of the thermal image is to be carried out, away from the test site (ie. off-line), a permanent record of the real time picture is required.

Thermograms can be recorded on-site by off-screen photography as described above. This method, however, is limited to a succession of single shot thermograms. For more critical and detailed analysis, or where conditions are rapidly changing as in air leakage detection, the 'video' output from the display monitor can be taken to a portable video recorder and stored on magnetic tape as a continuous record of the survey.

On many infra-red systems, the video recorder will only record the non-TV compatable image as shown on the monochrome monitor. Additional information such as thermal range, thermal level, object distance and air temperature, etc, must be recorded separately on paper. A useful alternative is to dictate the information onto the unused video sound track.

At the system's home base, surveys recorded in this way must be played back through the system's monochrome monitor for inspection or analysis. To maintain thermal level accuracy (particularly important for quantitative analysis), replay should be carried out using the same equipment as was used for recording. This will avoid shifts in the picture black level due to calibration variations between systems.

Also at this stage, image replay may be processed through an analogue to digital converter to enable subsequent computer analysis to be carried out.

In addition to the above, many modern infra-red cameras now provide a TV compatible output. This may be standard or require replay to take place through a scan converter. Either way, the resulting thermal image is PAL compatible and may be displayed or recorded onto standard television equipment.

4. THERMAL ANALYSIS - UNDERSTANDING THE THERMAL IMAGE

Interpreting the thermal image is the most important and demanding aspect of a thermographic survey. However, forward planning together with well defined survey aims will make this task easier and provide the results required.

There are three levels of infra-red survey and subsequent analysis.

4.1 Qualitative analysis

The first stage of inspection is the qualitative approach. This level of survey is ideal for locating hidden detail, for example the extent of missing insulation, the location of sub-surface pipes or construction detail.

It will be evident that the infra-red camera shows only the relative temperature difference in the image field. However, when used by a skilled operator on site, the real time thermal display may be studied and an interpretation made based on comparative analysis of the grey tone (or colour) picture. Given a knowledge of the structure under investigation, variations in the thermal image may be related to sub-surface detail and hence, defective areas of the building.

It should be noted, however, that once this 'simple' approach has been completed it is very difficult to extract further information because analytical parameters may not have been accurately measured and detailed thermograms not recorded.

4.2 Quantitative analysis

The second stage of inspection is the quantitative approach. In this, surface temperatures are calculated based on the thermal image and the necessary analytical parameters.

Conditions required prior to and for the duration of the survey are more stringent and although surface temperatures could be calculated on-site, it is more usual to record the thermal image onto video tape along with all the parameters needed for subsequent analysis in the laboratory.

In order to overcome the problem of relative temperature differences, an object of known temperature and emissivity (referred to as a reference source) is placed in the camera's field of view at the same distance from the camera as the object surface. By calibrating the image based on this reference, other surface temperatures can be found. A list of required parameters is shown in Figure A2.1. In addition, camera settings of thermal level, thermal range, aperture setting and filter position must all be noted.

Using this approach has several benefits, it overcomes the problem of analysis when different surface materials at the same temperature exhibit different thermal responses: thus accurate real surface temperatures can be calculated.

4.3 U-value assessment

The third stage of inspection is really an extension of the second stage. Following a quantitative survey, a full energy audit of a building may be carried out using the quantified thermograms as a guide. Additional information such as fuel and temperature monitoring together with on-site measurement of U-values may all be combined to assess a building's thermal performance.

4.4 Computer analysis

Appendix 2 describes the thermal measurement technique for the AGEMA 782 infra-red camera. When thermal images are to be quantified, Sections A2.6 and A2.7 give the practical formulae needed for analysis. Many infra-red systems incorporate computer based thermal analysis packages for image processing, see Figure 7. So in general, it is only necessary for operators to have a background knowledge of manual analysis techniques to understand the mechanisms of analysis in order to keep a check on the computer output.

Off-line image analysis is usually carried out at the thermographer's office on a menu driven thermal analysis computer. All the parameters necessary for analysis that were recorded on site are fed into the computer along with the corresponding digitised thermal image. (Figure 8 gives an impression of the computer's successive menu screens and a data entry screen.) Given this information, a number of analytical options are then available depending upon the complexity of the system used. Analytical packages for spot temperature, area and line-scan analysis and image enhancement are available.

The output from thermal image processors is a numeric print-out of data together with graphical and statistical information relating to the image analysed, see Figure 9. In addition, if a black and white or colour printer is connected to the system then a screen-dump (graphical printout) of the displayed thermal image is also possible. Images and results which may be required on future occasions may be stored on floppy disks.

The computer based thermal image processor has removed the need for thermographers to carry out long repetitive manual calculations on static thermograms. It also enables a high level of image enhancement and display facilities. However, the basic physics of thermography remain unchanged and should not be forgotten. A basic understanding of radiation theory and measurement technique will help reduce the risk of image misinterpretation at the computer.

5 CARRYING OUT THE SURVEY

With the first decision made as to the purpose of the thermographic inspection, the next is to decide whether to do it 'in-house' or employ a reputable firm. Both approaches have their merits and the choice will probably be made on cost, and the scale and duration of the work.

If the work is to be carried out 'in-house' then the first task is to purchase suitable infra-red equipment. Briefly, this will probably include the infra-red system complete with an analysis system, a temperature reference and possibly additional equipment such as a building optical inspection probe and a heat flux meter. The next stage requires the training of personnel to operate the equipment in the field of building inspection and here, most infra-red equipment suppliers operate training schemes.

When the survey is to be carried out under contact to a specialist firm, then the aims, results and level of report detail must be carefully specified because this will define the type of inspection required and ultimately the time and costs involved. It is for example, impossible to extract absolute surface temperatures from a qualitative inspection unless all the necessary parameters for analysis have been recorded.

The methodology used is common to all thermographic inspections, although the exact form the survey will take is dictated by the type of inspection and the required results.

Most important are the thermal influences to which the building is exposed both prior to and for the duration of the survey (see Section 6).

Next comes data collection. For simple qualitative or comparative inspections, when a written report is not required, on site analysis by a skilled operator and a site representative may be all that is required to satisfy the survey aims. However, when the results from the survey are to be analysed off-site and a written report given, then it is very important that all the necessary parameters for analysis are measured and recorded with each thermogram. In addition, the use of normal photographs of the site and inspected areas can be very useful for subsequent identification and explanation to staff not present during the survey.

6 CONDITIONS REQUIRED BEFORE AND DURING THERMOGRAPHY

The thermal conditions to which a building is exposed both prior to and during the infra-red survey are very important for a successful survey.

In order to minimise external climatic interference and to maximise thermal resolution the infra-red survey should, whenever possible, be carried out from inside the building. In general the following conditions should be met:

(a) For at least one 24 hour period before, and for the duration of the survey, the temperature difference between inside and outside must be at least 10°C. The outside air temperature variation should be small, and the internal air temperature should not vary by more than +/- 2.0°C.

(b) For at least 12 hours before, and for the duration of the survey, the building facade under investigation should not be exposed to sunshine sufficient to affect the results. The best conditions are usually found on cold overcast days.

(c) The external facade must not be visibly wet.

(d) For air leakage measurement the internal pressure must be less than external by at least 10 Pa.

For surveys carried out to determine paths of air leakage using mechanically generated pressure differences, the temperature for (a) may be reduced to 5°C. When an infra-red survey is to be combined with depressurisation air leakage measurement it may be necessary to relax the general conditions in order to complete the work. This will still enable a qualitative visualisation of the ingress of cold air as it enters and cools adjacent surfaces. Observation of the 'live' or recorded images will readily reveal the entry point of the cold external air; and the lowering of surface temperature with time will readily distinguish cooling due to air flow from conductive heat loss.

Where external thermography must be carried out for structural reasons or for preliminary measurements over large areas of wall, extreme care must be exercised during interpretation, see Section 7. In this case, even more stringent conditions must apply. In addition to 6(a) to (c) above consideration must be given to the following.

There must be no sunshine on the building element during thermography and preferably for at least 24 hrs before commencement.
If there has been sunshine on a building facade prior to thermography, then consideration must be given to 'historic' thermal influences. These include:

(i) the thermal mass of the structure;
(ii) the solar absorptivity of the surface features;
(iii) uneven surface shading due for example to trees, or other buildings;
(iv) the angle of facade features and the angle of the sun.

7 SOURCES OF INTERFERENCE DURING THERMOGRAPHY

There is a high risk, during the analysis of a thermographic survey, that all irregularities in surface temperature will be mistakenly identified as structural defects.

There are many occasions when the thermal image produced by the camera does not tell the whole truth! This may occur for 'real' reasons eg. a local variation in emissivity; or a totally misleading reason eg. a thermal reflection. In this section, some of these sources of interference will be discussed along with ways to avoid them.

Consider the passive infra-red thermographic survey carried out from within the building envelope. The internal air temperature should be at least 10°C above that of the outside air. Under these conditions heat leaves the building through the external envelope in proportion to the differing thermal resistances of the structure. Where the resistance is low, the internal surface may be expected to be colder than areas of high thermal resistance. It is, therefore, important that there are no unaccounted thermal influences over the areas of interest and that full consideraton be given to the physics of heat flow; ie. genuine variations in temperature which must be expected for instance in the vicinity of the ceiling and floor junctions and at the corners of walls.

Emissivity is the ability of a surface to emit thermal radiation. Fortunately most building matrials have a high emissivity; it is not, however, a constant (see Appendix 1) and different materials and finishes may change it. During the analysis of thermograms it is very important to consider any variation in emissivity over the surface under investigation for two reasons. Firstly the apparent surface temperature will depend directly on its emissivity and secondly, for opaque surfaces, the complement to emissivity is reflectivity; so the lower the emissivity the greater the reflective component and, therefore the greater the chance of 'seeing' a thermal reflection.

Thermal reflections are a common source of interference during analysis. However, it is very easy to identify the thermal reflection at the time the survey is carried out. The appearance of a reflection in the thermal image will (whether 'hot or cold') change its relative position depending on camera angle. Once identified, steps can be taken to eliminate the source. If the source is for example a radiator or light fitting it can be temporarily turned off a short time before measurements are taken. However, this must not cause the air temperature to fall so as to affect the distribution of surface temperature.

If the source of a thermal reflection cannot be eliminated, then a note must be made in the survey log so that errors are not made during analysis.

Surfaces with a very low emissivity, like metals, pose a real problem for thermography and there is no totally satisfactory solution. The image formed by the camera will be almost entirely made up of reflected radiation. If all the counter reflecting radiation can be accounted for then a reasonably good estimate of surface temperature may be made. The degree of error acceptable can only be determined by the nature and requirements of the survey. The other solution available is to alter the surface characteristics with paint, varnish or some other high emissivity coating prior to making measurements. This method will give good thermal results but may be totally unacceptable or impractical for real buildings.

Other sources of interference include sunshine through windows impinging on the surface to be thermographed either prior to or during the survey. If there is a risk of this, then blinds or curtains should be closed.

During thermography there must be no air currents, for example from open windows, open vents, warm or cold air ducts or fans, directed towards and likely to influence the surface to be thermographed.

Surface moisture, for instance, condensation will also have an appreciable effect on surface temperature by changing the local transmission of heat at the surface and causing cooling by evaporation. The occurrence of this risk will be greater over areas concealing genuine defects like thermal bridges and missing insulation, however, any surface moisture must be carefully noted during thermography.

Major sources of interference described above can normally be detected and eliminated prior to the start of a survey. If it is not possible to protect a surface of interest from sources of interference, then the position, condition and detail of the problem must be carefully noted on each occasion in the survey log in order to minimise misinterpretation and assessment of the result.

8 PRACTICAL EXAMPLES IN THE USE OF THERMOGRAPHY

8.1 Energy consumption in buildings

Heat is lost from a building in many ways, as shown in Figure 10. Losses through the fabric are quantified by the thermal transmittance or U-value.

The greater the U-value, the greater the heat loss through the building envelope. In practice a building will consist of many areas of varying U-value. The total heat loss through the building fabric is found by multiplying U-values and areas of the externally exposed parts of the building, and multiplying the result by the temperature difference between inside and outside.

In addition to conductive heat loss, a building will also lose heat by the ingress of cold external air combined with the associated loss of warm internal air, quantified as ventilation losses. Ventilation, expressed in air changes per hour, is a design factor varied to maintain indoor air quality depending on the activity carried out within the building or part of a building. Building ventilation is provided naturally or mechanically, together with adventitous losses which occur through points of air leakage in the building.

By using thermography, many aspects of buidling heat loss may be visualised and quantified. The following examples demonstrate some common applications.

8.2 Insulation defect detection

Within the building industry, the use of infra-red thermography has gained in usefulness as a means to monitor and evaluate modern insulation techniques and standards. Qualitative thermography can provide a rapid method of assessing the in-situ quality and performance of insulation.

Before such a survey is carried out, the requirements of Section 7 must be met. Insulation performance can be deduced by observing variations in surface temperature, see Figure 11. Areas of reduced insulation will be cooler in comparison to the surrounding internal surfaces, so variations in grey tone (or colour) over the thermal image can be taken as variations in the thermal properties of the object. When used by a skilled operator, defects may be quickly identified and, where need be, remedial treatment applied. Figure 12 shows a very distinctive cold area on the ceiling of a house, where the painted surface has a uniform emissivity. In this case, however, the variation in surface temperature aligns with an area which has been left clear of insulation to prevent freezing of the cold water storage tank in the loft.

As shown, the analysis of most qualitative thermograms involves comparison to determine areas of reduced insulation. In most cases this approach is satisfactory, but occasionally, due to unusual circumstances, comparison can be misleading, this is particularly relevant when carrying out external thermography. On facades of uniform material and construction exposed evenly to the prevailing climatic conditions, comparative analysis of thermograms should be satisfactory. However, if for example, a facade has surface features of differing colours, then surface temperature may be influenced by the materials differing absorptivity to solar radiation. In heavyweight constructions, a temperature variation generated by solar radiation may be retained for many hours after sunset, see for example Figure 13. It follows, therefore, that 'historic' differences in external surface temperature must be expected, particularly for facades of different materials or orientation, and must be taken into consideration when interpreting external thermography measurements.

For a more detailed analysis, perhaps linked to an energy audit, a quantitative survey may be carried out, but for this, the prevailing conditions both indoors and outdoors must be carefully monitored. Consideration must be given to the thermal mass of the building construction, and all the parameters necessary for the subsequent analysis carefully measured and logged. In the UK, the absence of a British Standard for thermography means that this guide plus ISO/DIS 6781[1] is the best source of guidance, supplemented by factors related to British building and climatic conditions.

Figure 14 shows a quantified thermogram, the internal leaf of this cavity-filled wall shows clearly an area of reduced insulation. By analysing the image, surface temperature can be calculated for the two defined areas. In this case, area 1 has an average surface temperature close to the internal air temperature indicating a high degree of insulation, whilst area 2, the adjacent area has an average surface temperature 1.5°C lower, indicating a substantial reduction in insulation.

Quantitative analysis of a thermogram may be taken one stage further by combining the infra-red technique with that of U-value measurement using a heat flux meter (see Section 9). Using the quantified thermogram as a guide, the heat flux sensor plate is located on a representative area of a wall. The U-value obtained over a long averaging period is then representative for the area indicated by the thermogram. In this way, comparison with design values can be made.

Before remedial insulation treatment is applied to any building based on the findings of thermography, it may be desirable to carry out a structural survey to investigate the cause or reason for the deficiency. In such cases the thermogram may be used as a guide to the accurate positioning of inspection equipment such as industrial optical probes. An internal inspection will then verify absolutely the absence of insulation and also identify any structural defect which may be the underlying cause of the problem.

The requirement for an infra-red thermographic survey with a 10°C temperature difference between indoors and outdoors means that an inspection cannot be carried out on a building until it is complete and the heating system commissioned. However, when confirmation of a suspected defect is required prior to completion of a building or when full heating is not available, then local discrete heaters may be used, see Figure 15. In general these may be panel heaters, electric 'blankets', radiant heaters, etc. in fact any form of heat that can generate a temperature difference sufficient to visualise the defect, (see wall tie detection in Section 8.5 (Figure 27)).

The length of time the heating will be required prior to the start of a survey will depend on the thermal mass of the object and the nature of the defect. In all cases, however, measurements from the survey can only be considered qualitative because, unless the object is very lightweight, thermal equilibrium will not be reached.

8.3 Air leakage detection using thermography

Modern construction techniques and practices usually attempt to reduce natural ventilation to a minimum and in some cases mechanical ventilation coupled with heat recovery has replaced the need for natural ventilation. In such constructions, uncontrolled infiltration of cold external air is both undesirable and a waste of energy.

Detecting air leakage within a building by thermography relies on observing the lowering of the surface temperature on parts of the wall adjacent to the leakage point. The magnitude of this change in temperature depends upon:

(a) the nature and size of the point of leakage;

(b) the pressure differential across the construction;

(c) the temperature difference between indoors and outdoors.

Due to the irregular effects of wind on a building, the most difficult parameter to establish is the naturally occurring pressure differential. Pressure conditions in practice are relatively varied and complex, and airflow into a building through leakage paths cannot be guaranteed. The temperature difference between indoors and outdoors is, however, more easily established and should be at least 5°C.

When a detailed study of air infiltration is to be undertaken, it is preferable to stabilise the pressure differential by the use of mechanical extract fans. Such equipment is already used to measure whole building air leakage characteristics, see Figure 16; when combined with the qualitative thermographic technique points of air leakage may be quickly identified and, where need be, remedial treatment applied.

The effect of mechanical air extraction is to reduce, in a controlled way, the pressure within a building to below that of the external air and hence to increase the rate of airflow through any air flow paths through the building envelope. Under such circumstances the direction of the flow is inwards and the cold air cools the surfaces close to the point at which it enters the building. If thermograms are taken before and at intervals after the building is depressurised the colder area is seen to become larger as the incoming air progressively cools a larger surface area. This technique enables cooling due to airflow to be distinguished from heat loss due to conduction through the fabric.

Figure 17(a) is a typical thermogram of an air leakage path at a wall to ceiling joint under naturally occurring pressure differences. Figure 17(b) is the same view taken 10 minutes later with a mechanical pressure difference of 45 Pa applied across the building envelope. It is clear that the cold area of this joint has increased substantially as more of the internal surface becomes cooled by the induced inflow of cold air.

Points of air leakage which may have remained undetected under naturally occurring pressure differentials because of low or positive internal pressures may also be found by this means. Under depressurisation Figure 18 shows a large area of cooled surface on an open plan pitched roof, this would indicate possibly an incomplete or damaged vapour barrier. Under natural pressure differentials, however, the area at the wall to ceiling joint was just visible but the extent of the damage was impossible to assess, and could easily have been missed.

8.4 Thermography and heat loss through windows

Windows, although apparently simple in construction, are in fact thermally quite complex; and there are many ways in which their thermal performance can be improved.

Heat is lost from a window by conduction and through paths of air leakage. Heat loss from draughts around the frame, through hinges and ill-fitting openable windows can be detected using the air leakage infra-red technique.

Fabric losses can also be examined by thermography provided the short wavelengths transmitted through the glass are eliminated by the use of a suitable spectral filter.

Using thermography, a useful comparison can be made between the various forms of window insulation, and given the rapid thermal response of window constructions, the technique can be extended to quantify heat loss in terms of a U-value.

Figure 19 is a thermogram of a typical single glazed, metal framed window. By using a glass spectral filter (Cut-on wavelength 4.8 μm) and detailed analysis, (see Section 9), a mean surface temperature of 13.5°C is obtained within the marker boundary. Given that the heat transfer is close to steady state and assuming an internal heat transfer coefficient of 0.12 W/m² K, an estimated U-value for the window of 5.0 W/m² K is obtained from the internal and external air temperatures and the calculated surface temperature ie close to the expected value.

For comparison, Figures 20(a) and 20(b) show a good quality wooden framed double glazed window. the surface temperature of the glazed surface was calculated to be 11.3°C. This yields an estimated U-value of 3.5 W/m² K, which is in the range expected for double glazing with a small air gap (6 mm). The frame temperature of 18.3°C indicates an approximate U-value of 0.5 W/m² K. This gives an average U-value for the window, including frames, of 2.4 W/m² K close to the design value of 2.5 W/m² K.

The effects of modern methods of reducing heat loss from windows can also be demonstrated by thermography. Figure 21(a) is an external thermogram comparing conventional and 'low emissivity' (low 'e') double glazing. Clearly, the lower surface temperature of the argon filled low 'e' glazing can be clearly identified. From comparative internal thermograms, the U-value of the double glazed units was estimated to be 1.56 W/m² K, close to the quoted value of 1.6 W/m² K. Figure 21(b), however, shows the comparison between two low 'e' windows with and without argon filling in the 'air-gap'. The low 'e' window without argon has an estimated U-value of 1.84 W/m² K, again close to the quoted value of 1.9 W/m² K.

The effect of curtains can also be examined. Figure 22 and Figure 23 are thermograms of two adjacent windows of the type shown in thermogram Fig 19, but with curtains hung within the window reveal. Figure 22 is an unlined cotton curtain, Figure 23 is an identical curtain with a loose lining. By examining the two pairs of curtains, hanging under identical conditions, direct comparison can be made about their thermal performance. Clearly the lined curtain provides better insulation as indicated by the warmer internal surface; translated to an estimated U-value gives an improvement of 0.5 W/m² K compared to the unlined equivalent.

In addition to the use of thermography to examine the thermal performance of windows, the technique can also be used to investigate the thermal environment around windows. Traditionally, central heating radiators are placed beneath windows to help reduce the effect of cold convection currents on occupants. This practice, however, can have a dramatic effect on the thermal environment around the window.

Figure 24 is an internal thermogram of a single glazed window with closed curtains, with no radiator under the window, the curtains have an average surface temperature 3.5°C below the room air temperature. Figure 25, however, shows the adjacent window, which has a radiator beneath, to have an average surface temperature 0.5°C below air temperature. In this particular case the rise in curtain temperature will lead to an increase in heat loss at the window of about 30%. Thus, thermography may be used to demonstrate how the difference in the local micro-climate can affect the heat loss through a component.

8.5 General building applications for thermography

In addition to testing the thermal performance and airtightness of buildings, thermography is principally a diagnostic tool when used within the building and building services industry. The range of application is extensive: provided an object exhibits variations in surface temperature which can be related to its physical state or position, then thermography can be used to locate or diagnose the underlying problem.

Objects for investigation by thermography may be grouped into two categories, passive objects and active objects. Generally most building components are passive; heat is not generated within the structure but conducted through from one side to the other. An example of visualising hidden detail is shown in Figure 26, where the position of the mortar joints and perpends between the internal block construction of this plastered cavity wall is clearly revealed.

Confirmation of the position and integrity of wall-ties may also be investigated in a similar way, see Figure 27. Most conventional wall-ties are metal and can be readily located using metal detectors. However, although these will correctly locate a metal tie, they cannot indicate the physical condition of the tie. The most serious defects are likely to be damage during construction or corrosion in service leading to a reduction of effective cross-sectional area of the tie. By viewing the cold face of a warmed cavity wall, (current experimental work suggests temperature difference about 40-50°C. Adderson and Hart[2]), a detailed study of localised hot spots will indicate the condition of wall-ties. The thermogram in Figure 28 clearly shows the position of four wall-ties on a standard grid pattern. Any absence of hot spots on the standard grid patern may then indicate the position of defective or missing ties. Within a defined suspect area additional inspection may be carried out as required, using a metal detector or a structures inspection optical probe.

Active components within a building structure include the heating system and thermography may be used to examine the efficiency and condition of a system in situ. The thermogram in Figure 29(a) shows the distribution of underfloor heating pipes, an application useful for position location, identifying blockages and leaks and for assessing overall temperature distribution. In this example of a ground floor heating installation, the plastic pipes are situated beneath a 50 mm concrete floor screed. Initially, however, the surface temperature distribution was so even that a step change in the circulated water temperature was necessary to highlight the pipes. Figure 29(b) shows the first floor pipes of the same installation located beneath 25 mm of chipboard where not only are the pipes very clearly defined, but so also are the metal heat spreader plates located at intervals over the pipes.

Figure 30(a) shows the heat distribution from a convector/blower heater. Although the infra-red camera cannot 'see' warm air, the distribution of heat from this low level fan assisted warm air system can be clearly seen as it warms the floor area in front of the heater. The thermogram Figure 30(b), however, shows a similar heater with an uneven temperature distribution, clearly indicating a blockage in the air duct at the centre.

Thermography may also be used to diagnose and locate faults in electrical installations. An example is the detection of overheating connector blocks in the trunking of a high level lighting circuit. Using the infra-red camera from the ground, an affected joint section may be located for closer inspection, see Figure 31(a). With the connector removed from the trunking, Figure 31(b) clearly shows the heat generated within the connector block indicating a high resistance joint. By using thermography in this way, planned preventative maintenance can take place to eliminate potential hazards.

Thermography has also been successfully used to locate dampness on the down stream side of earth embankment dams, (Tedd and Hart[3]). By utilising the naturally occurring seasonal and diurnal temperature variation together with differences in target emissivity a 'remote' survey of the down stream slope, provided it is not obscured by vegetation, can identify areas of dampness, see Figure 32. Traditional inspection methods may then be used to determine the source of the dampness, verify the severity and initiate repair.

The examples shown give an indication of the variety of naturally occurring applications for thermography within the building industry, but they are by no means exhaustive. There are also a number of ways in which object surfaces may be artificially heated in order to visualise defects, see

Section 8.1 plus, (Adderson; Hart[2]), (Reynolds [4], and (Hillemeier [5]), including radiant heating of surfaces and induction heating of reinforcing bars.

Other more recent examples include the location of chimney flues prior to renovation and the flow visualisation of hot air from a locomotive.

9 COMBINED USE OF THERMOGRAPHY WITH A HEAT-FLUX-METER OR AN OPTICAL PROBE

9.1 Thermography plus a heat flux meter to provide quantitative heat loss measurement

For lightweight responsive components where unidirectional and stationary heat flow can be established, thermography may be used directly to establish surface temperature. The results may then be extended to estimate U-value and determine heat loss in terms of W/m^2, Section 8.4. At all times in this process, careful consideration must be given to the accuracy of the thermal image and the additional parameters needed to carry through such a calculation. For example, see Section 8.4 the estimation of U-value applied to a wooden double glazed window.

For the calculation of U-value, the numerical value for the internal surface resistance, Rsi, may be taken from guide values, (CIBSE[6]) or calculated to suit individual applications, (Petterson[7]), and (McAdams[8]).

In heavyweight non-responsive building components, steady state thermal conditions rarely occur. The effect of diurnal variation coupled with cyclic heating patterns combine to ensure a continually changing thermal environment. For building with a large thermal mass, the heat flow through the structure (the thermal conductance) is not in step with the temperature difference across the structure. Under such conditions, an estimating of U-value based on an infra-red image captured at one instant in time, may be very misleading.

One way to overcome this latter problem is to combine quantitative analysis of a thermogram with that of U-value measurement using a heat flux meter, see Figure 33. Using the quantified thermogram as a guide, the heat flux sensor plate is located on a representative area of a wall. The U-value may then be derived from the time averaged heat flux divided by the average air temperature difference between inside and outside. Provided this cumulative process is continued long enough for the thermal mass to have a negligible influence, then this ratio ultimately converges to the U-value (Anderson[9]), which is then representative for the area indicated by the thermogram. In this way, comparison with design value can be made. Figure 34 shows a graph of U-value against time for a typical uninsulated brick/block cavity wall. The rapidly changing instantaneous U-value can be clearly seen compared to the long term running average. At least five days are necessary in this particular case before a stable U-value is obtained.

By using this combined approach, a method can be provided to investigate the thermal performance of a structure and derive a U-value in situ.

9.2 Thermography plus an optical probe to provide physical or structural inspection

The thermal images produced during a thermographic survey comprise a series of 'thermal maps' of the surfaces inspected. Skilled operators can then, with the aid of structural details, and/or plans, deduce information about sub-surface defects from surface temperature abnormalities. There are occasions, however, when the exact underlying defect cannot be positively determined. For example, a cold internal surface of a cavity filled wall may very well be due to missing insulation; but equally the insulation may be missing due to a partially blocked, or bridged, area of cavity. In these circumstances, it may be necessary to make a physical inspection.

Unfortunately, the very nature of a physical inspection means 'damage' to the structure (holes drilled or bricks removed). One way to minimise this damage is to use an industrial optical probe, see Figure 35. Using the thermal image as a guide, a small hole (approximately 13 mm) is drilled in the mortar joint on the external facade and the instrument inserted, Figure 36. The fibre optic light guide and powerful light source provides ample illumination for inspection and if necessary photography, see Figure 37.

Using this technique, positive identification of sub-surface damage can be obtained while minimising damage to the structure. This is achieved due to the small access hole and the precise area location provided by the infra-red camera.

10 CONCLUSIONS

Infra-red thermographic systems have advanced rapidly in recent years, particularly in the field of image analysis. At the same time the demand for non-destructive testing has also increased; and for buildings, modern insulation techniques and standards have reduced heat requirements to below that previously necessary.

This report has outlined some of the many uses to which infra-red thermography can be put in the thermal performance testing of buildings, structures and building components. These uses are by no means exhaustive, and many new applications are being found all the time.

As a non-destructive qualitative tool, thermography's ability to rapidly visualise variations in surface temperature are invaluable. However, interpretation of the thermal image is crucial to the success of any survey, so care and forethought must be given to the survey aims, the prevailing environmental conditions and the presentation of the thermal image. In addition, for the quantitative technique, all the parameters necessary for off-line analysis must be carefully measured and recorded. Ultimately, it will be the accuracy and precision with which these parameters are measured that will determine the accuracy of the final result.

As shown, the infra-red technique provides a rapid, remote sensing and non-destructive test method for diagnosing temperature related defects. However, there are occasions when verification may be required before remedial or legal action is undertaken. In these cases the thermal image may still be used, but now as a guide to the placement of additional instrumentation, such as an optical probe for internal inspection or heat flux meter for on-site U-value determination.

Continued advances in infra-red systems, techniques and computer enhanced analytical systems are taking place giving rise to a reassessment of new or improved application areas. However, it is the skilled system operator whose job it is to carry out the survey, get the best from the equipment and to interpret the survey findings. The results from a badly designed or executed survey will lead to misinterpretation no matter how much 'high tech' equipment is used during analysis. The skill of the operator is thus of equal importance as the equipment used.

APPENDIX 1 Thermographic properties of materials

A1.1 Blackbody radiation

A blackbody is defined as an object which absorbs all incident radiation striking it regardless of wavelength. From Kirchoff's Law it can also be shown that a blackbody is equally capable of emitting radiation at all wavelengths.

Radiation emitted from a blackbody can be described by the following three expressions:-

1. The spectral distribution of the radiation from a blackbody can be described by Planck's law

$$E_{\lambda T}=2\pi hc^2\lambda^{-5}10^{-6}/(\exp(hc\lambda^{-1}K^{1}T^{-1})-1) \qquad (Wm^{-2}(\mu m^{-1})) \qquad \textbf{Equation 1}$$

Where $E_{\lambda T}$ = Spectral blackbody radiation at the wavelength λ (μm) and temperature T (K).

c = Velocity of light 3.0×10^8 (ms^{-1})

h = Planck's constant 6.63×10^{-34} (Js)

K = Boltzmann's constant 1.38×10^{-23} (JK^{-1})

T = Thermodynamic temperature (K)

Planck's formula, when plotted graphically (see Figure A1.1) for various temperatures, produces a family of curves. Following any particular

Planck curve, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at a wavelength λ max, and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which the maximum occurs. Superimposed on Figure A1.1) are the wavebands which are used for thermal imaging cameras, 3.0 to 5.6 μm and 8.0 to 14.0 μm.

2. By differentiating Planck's formula (Equation 1) with respect to λ, the wavelength at maximum spectral emittance of radiation is given by Wien's displacement law

$$\lambda_{max} = 2898T^{-1} \qquad (\mu m) \qquad \textbf{Equation 2}$$

At ambient room temperature (300K) the peak of the radiant emittance lies at 9.7 μm, whilst at 343K, the temperature of a hot central heating radiator, the peak lies at 8.5 μm.

3. By integrating Planck's formula from $\lambda = 0$ to $\lambda = \infty$, the total radiant emittance E for a blackbody is given by the Stefan-Boltzmann law

$$E=\sigma.T^4 \qquad (Wm^{-2}) \qquad \textbf{Equation 3}$$

Where $\sigma=5.67 \times 10^{-8}$ $(Wm^{-2}K^{-4})$

This then is the Stefan-Boltzmann formula, which states that the total emissive power of a black body is proportional to the fourth power of its absolute temperature. Graphically, E represents the area under the Planck curve (Figure A1.1) for a particular temperature.

A1.2 Non-blackbody emitters and emissivity

So far only blackbody radiators and blackbody radiation have been discussed. Unfortunately, 'real' objects never comply with these laws over an extended waveband, although a surface may approach blackbody behaviour within a given spectral region. for example, white paint appears perfectly 'white' in the visible light spectrum, but beyond 3 µm it is almost black.

There are three processes which can occur which prevent a 'real' object from acting as a blackbody. A fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted.

These three fractions are all more or less wavelength dependent, but for any given wavelength must add up to unity. So we have the relation

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

Where the spectral absorptance α_λ = the ratio of the spectral radiant power absorbed by an object to that incident upon it,

the spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it,

the spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

For a blackbody $\alpha_\lambda=1$, $\tau_\lambda=0$, $\rho_\lambda=0$

In building thermography, all surfaces of interest are non-blackbody emitters and most are opaque (see A1.4 and Section 8.3) to infra-red radiation over the wavelength range 3.0 to 5.6 μm, so the above relation simplifies to:-

$$\alpha_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, ε, is used to describe the fraction of the radiant power of a blackbody produced by a non-blackbody object at a specific temperature.

The spectral emissivity ε_λ = the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength.

According to Kirchhoff's law, for any material, the spectral emissivity and spectral absorptance of a surface are equal at any given temperature and wavelength. That is $\varepsilon_\lambda = \alpha_\lambda$. For an opaque surface:-

$$\varepsilon_\lambda + \rho_\lambda = 1$$

Emissivity is a function of the thermodynamic temperature of the surface T, the wavelength of radiation λ and the direction of radiation θ (from perpendicular to the surface)

$$\varepsilon = f\ (T, \lambda, \theta)$$

Over the temperature range experienced in building thermography, -10 to 40°C, the temperature dependence of ε can be ignored. Also, as a wavelength range for the camera can be specified (ie 3 to 5.6 μm), we can write: $\varepsilon + \rho = 1$ for an opaque surface viewed at right angles to the surface.

The angular dependence of emissivity, however, is not a constant; in fact the directivity of the coefficient of emission varies with angle and material. The emissivity of non-metals is high and practically constant for angles between 0 degrees and about 65 degrees from the perpendicular, after that emissivity declines, see Figure A1.2. For angles greater than about 70 degrees, the value of ε drops to zero very quickly. for metals, however, the reverse is true, emissivity is very low between 0 to 40 degrees. After which the value of ε increases, see Figure A1.3.

A diffuse surface is characterised by the fact that the value of emissivity is independent of the direction of radiation. In the field of building thermography, radiation emitted by a surface can normally be considered diffuse. Therefore, if the surface is grey and diffuse it should be possible to use just one value of emissivity for the assessment of radiation emitted by the surface, see Table A1.1.

A1.3 Greybody emitters

Non-blackbody emitters, for which the value of ε is independent of the wavelength are known as greybody emitters, the emissivity is then a constant less than one. Taking into account ε for a greybody radiator, the Stefan-Boltzmann formula becomes:

$$E_e=\varepsilon_1 \sigma T_1^4 \qquad \textbf{Equation 4}$$

Where E_e = Energy flux emitted per unit area, (Wm^{-2})

σ = Stefan-Boltzmann constant, = 5.67×10^{-8} $(W/(m^2K^4))$

T_1 = Temperature of the surface, (K)

ε_1 = Emissivity of the surface

The above formula accounts for the energy flux emitted from the surface of an object due to its thermodynamic temperature. Because a greybody emitter is not a perfect radiator, that is ε does not equal unity, a second energy flux path must be added to the emitted energy path. This second energy flux path is a result of the object surface receiving energy from the surrounding surfaces, which is then re-emitted from the object surface. The re-emitted energy flux is

$$E_r = \rho_1 \varepsilon_2 \sigma T_2^4 \qquad \textbf{Equation 5}$$

Where E_r = Energy flux reflected, (Wm^{-2})

ρ_1 = Reflective index of the surface

T_2 = Temperature of the surroundings, (K)

ε_2 = Emissivity of the surroundings.

However, for an opaque surface Kirchhoff's law states that:

$$\rho_1 = 1 - \varepsilon_1 \qquad \textbf{Equation 6}$$

The total energy flux E, received from an object surface by the infra-red camera is therefore:

$$E = E_e + E_r$$

so $$E=\varepsilon_1\sigma T_1^4 + (1 - \varepsilon_1)\varepsilon_2\sigma T_2^4$$ **Equation 7**

An infra-red camera detects the total energy flux E, from an object surface. Providing ε_1, ε_2 and T_2 are known along with the camera calibration characteristics, it is possible from Equation 7 to obtain a measure of the object's surface temperature, T_1.

A1.4 Transparent materials as emitters

So far only opaque objects have been considered ie. Transmittance = 0. Within a building framework, however, there are some materials which are partly transparent to infra-red radiation within the 3 to 5.6 µm waveband; the most common being glass.

Glass is obviously transparent in the visible part of the spectrum, 0.4 to 0.7 µm, but its transparency extends into the mid infra-red region up to about 4.8 µm.

When the surface of glass is viewed by a short wavelength infra-red camera, the thermal image formed consists of emitted and reflected radiation plus a transmitted component. The true temperature of the glass surface viewed by the camera cannot, therefore, be obtained as the image formed is influenced by radiation passing through the glass.

If the true surface temperature of a glass surface is to be obtained, then the transmitted component of the thermal image must be eliminated. This can be achieved by introducing a spectral filter into the radiation beam within the infra-red camera. A spectral glass filter has a cut-on wavelength of 4.8 µm, therefore preventing all radiation below this wavelength, ie. the transmitted radiation, from reaching the infra-red detector. The resulting thermal image is, therefore, formed from only the emitted and reflected component of the received radiation.

The addition of the spectral filter does mean that very little thermal energy is available to form an image within the narrow wavelength band of 4.8 to 5.6 µm, and extreme care must be taken particularly when viewing the windows of a building where surface temperatures are typically in the range 5 to 15°C.

With the exception of glass and some plastics there are few other commonly encountered transparent materials in building thermography, however, in general ALL surfaces should be carefully examined, and their infra-red properties assessed, prior to the commencement of any thermographic survey.

A1.5 Emissivity values for some common building materials

Common building materials with values of emissivity over the wavelength range 3 - 5.6 μm.

Fibre board	0.85
Plywood	0.84
Timber (general)	0.85
Plasterboard	0.90
Gypsum plaster (dry)	0.92
Paint oil black mat.	0.95
Paint oil (mean) colours matt.	0.90
Paint emulsion black matt.	0.95
Paint emulsion colours matt.	0.92
GRP black gloss	0.88
GRP white gloss	0.87
Wall paper (general)	0.87
Wall paper, vinyl (general)	0.89
Bricks, flettons	0.90
Facing bricks, red	0.91
Facing bricks, yellow	0.74
Building blocks (Thermalite)	0.92
Concrete	0.92
Aluminium foil (new)	0.09
Radiator foil (proprietory)	0.38
Water	0.96
Ice (smooth)	0.96
Snow	0.85

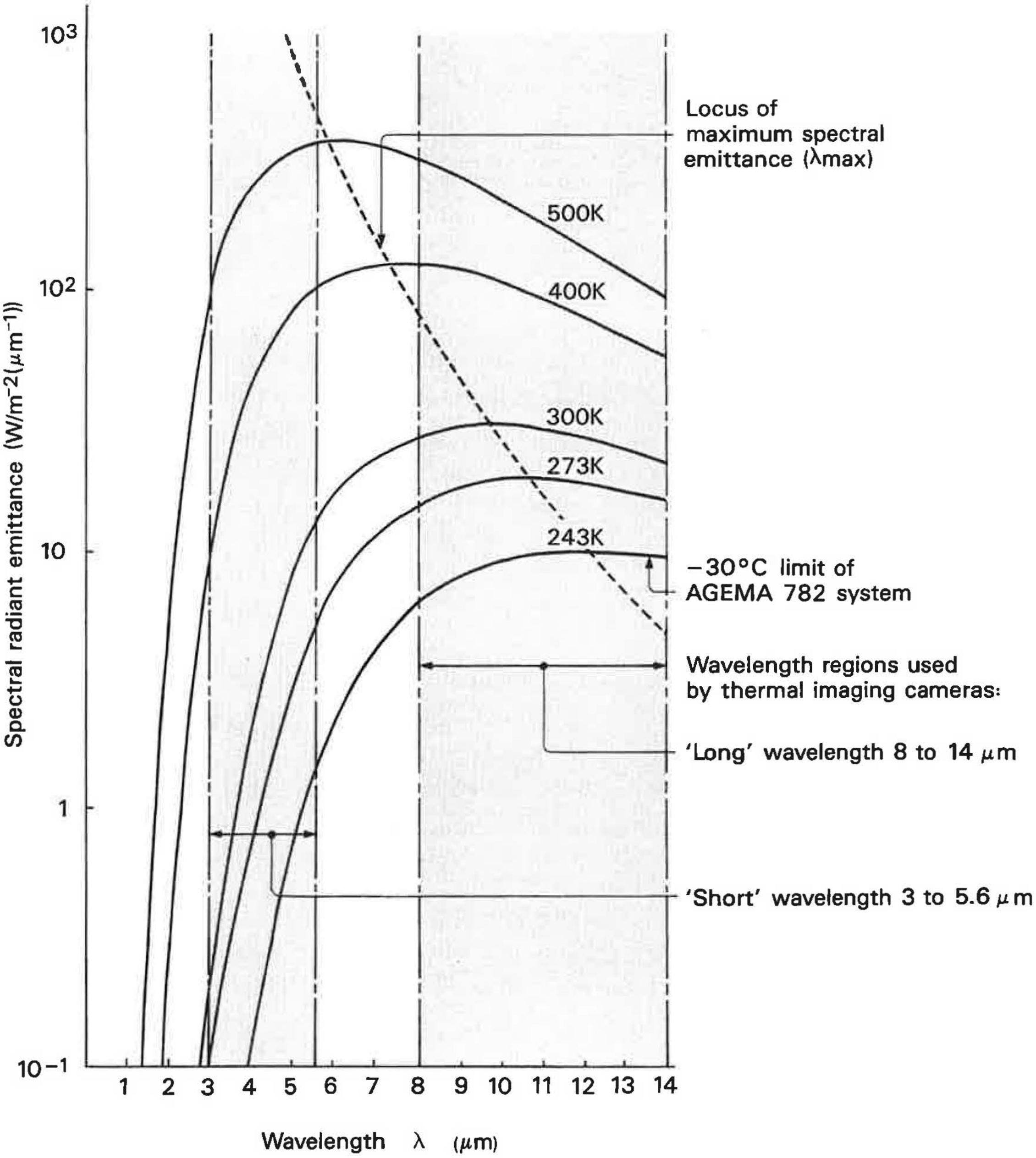


Figure A1.1 Blackbody spectral radiant emittance according to Plank's law, (Equation 1), plotted for various temperatures

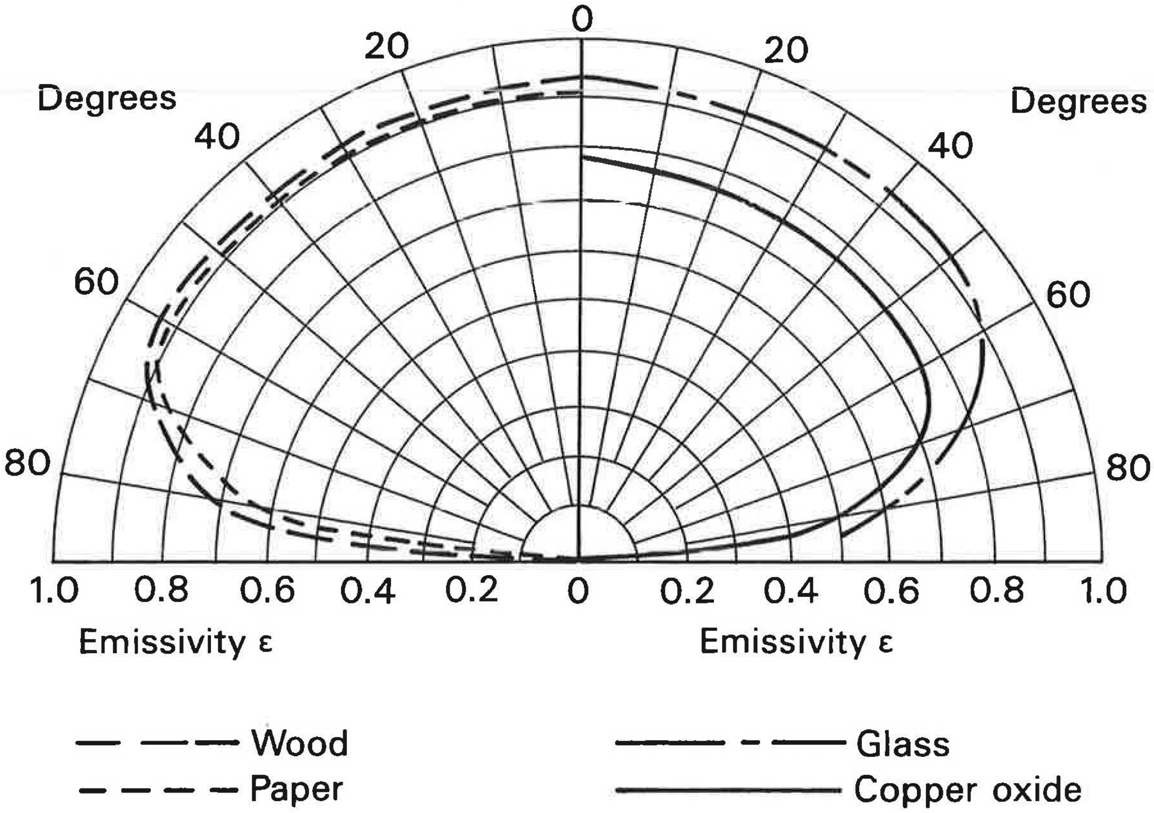


Figure A1.2 Angular dependence on emissivity for some non-metals

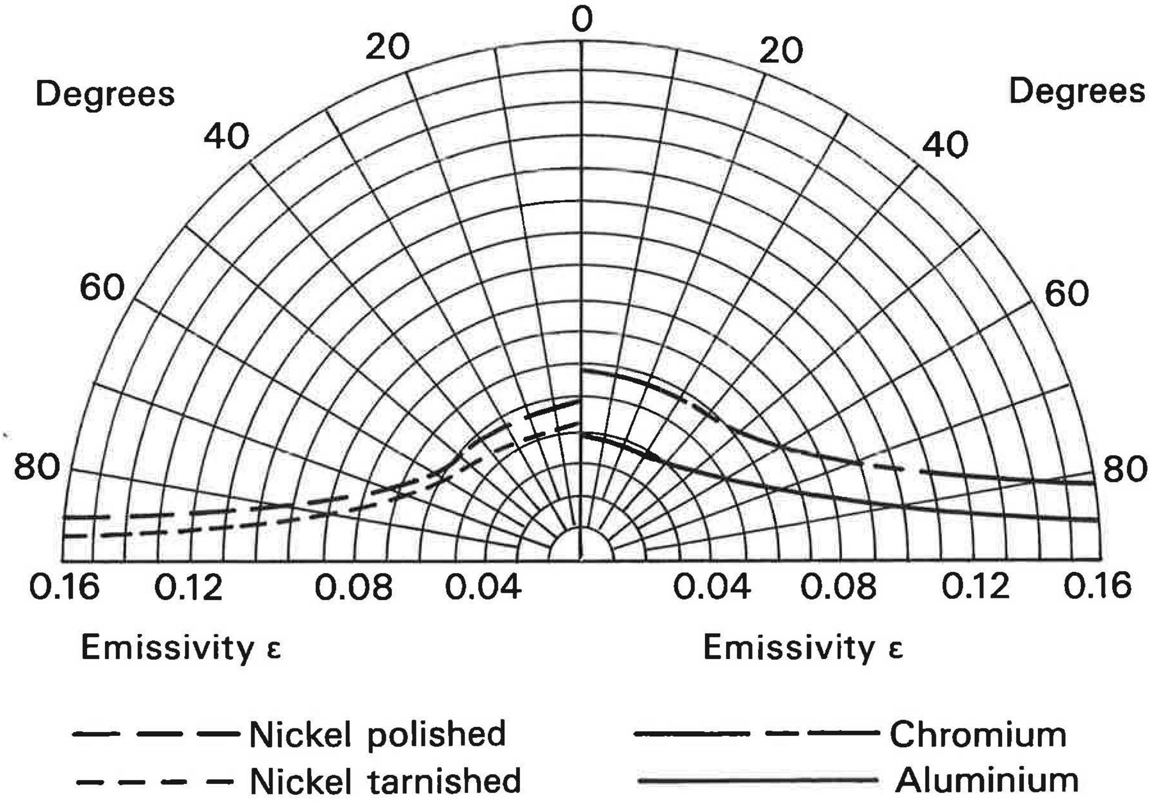


Figure A1.3 Angular dependence on emissivity for some metals

APPENDIX 2 Thermal Measurement Techniques using an AGEMA Thermovision Camera

A2.1 Derivation of the basic formulae

Consider an object with a surface temperature of T_1 and an emissivity of ε_1, surrounded by counter-reflecting surfaces with a temperature of T_a and an emissivity of ε_a. From Equation 7 the following energy flux will be emitted:-

$$E_1=\varepsilon_1\sigma T_1{}^4+(1-\varepsilon_1)\varepsilon_a\sigma T_a{}^4 \qquad \textbf{Equation 8}$$

Consider the surface radiating E_1 as the object surface.

If during thermography there is a second surface with a temperature T_2 and an emissivity ε_2, then the emitted energy flux for this surface will be:

$$E_2 = \varepsilon_2\sigma T_2{}^4 + (1 - \varepsilon_2)\varepsilon_a\sigma T_a{}^4 \qquad \textbf{Equation 9}$$

Consider the surface radiating E_2 as the reference surface, see Figure A2.1.

If isotherms are imposed over the image of the two surfaces with temperatures T_1 and T_2 the isotherm difference measured on the display screen, $\Delta I_{1,2}$ will be expressed as:

$$\Delta I_{1,2} = k\ (E_1 - E_2) \qquad \textbf{Equation 10}$$

Where k is a constant which is dependent on the properties of the camera. If Equations 8 and 9 are substituted into Equation 10:

$$\Delta I_{1,2}=k[\varepsilon_1\sigma T_1{}^4+(1-\varepsilon_1)\varepsilon_a\sigma T_a{}^4-\varepsilon_2\sigma T_2{}^4-(1-\varepsilon_2)\varepsilon_a\sigma T_a{}^4] \qquad \textbf{Equation 11}$$

If ε_a is put equal to 1

$$\Delta I_{1,2}=k\varepsilon_1\sigma(T_1{}^4-T_a{}^4)-k\varepsilon_2\sigma(T_2{}^4-T_a{}^4) \qquad \textbf{Equation 12}$$

where $k\sigma(T^4) = f(T)$

Where the function f(T) is determined from the camera's calibration curves, see Figure A2.2, for the appropriate objective aperture, then:

$$\Delta I_{1,2}=\varepsilon_1[f(T_1)-f(T_a)]-\varepsilon_2\ [f(T_2)-f(T_a)] \qquad \textbf{Equation 13}$$

Solving Equation 13 for $f(T_1)$ and substituting the absolute isotherm difference Δ_{ior} as the difference between the object and reference temperatures:

$$f(T_1)=\frac{\Delta_{ior}}{\varepsilon_1}+\frac{\varepsilon_2}{\varepsilon_1}f\ (T_2)+f(T_a)\ \left[1-\frac{\varepsilon_2}{\varepsilon_1}\right] \qquad \textbf{Equation 14}$$

Where T_1 Temperature (object) at point 1 on the thermal image (°C)

T_2 Temperature (reference) at point 2 on the thermal image (°C)

T_a Ambient air temperature (°C)

ε_1	Emissivity at point 1 on the thermal image.
ε_2	Emissivity at point 2 on the thermal image.
Δ_{ior}	Difference in isotherm units between the isotherm markers on the grey scale for the object and reference points on the thermal image.
$f(T_1)$	Value of the function according to the calibration curve of the camera for T_1.
$f(T_2)$	Value of the function according to the calibration curve of the camera for T_2.
$f(T_a)$	Value of the function according to the calibration curve of the camera for T_a.

Parameters

T_1 = Object temperature

ϵ_1 = Object emissivity

T_a = Temperature of counter-reflecting surfaces
(Generally Air Temperature)

ϵ_a = Emissivity of counter-reflecting surfaces

T_2 = Reference temperature

ϵ_2 = Reference emissivity

D_o = Camera to target distance

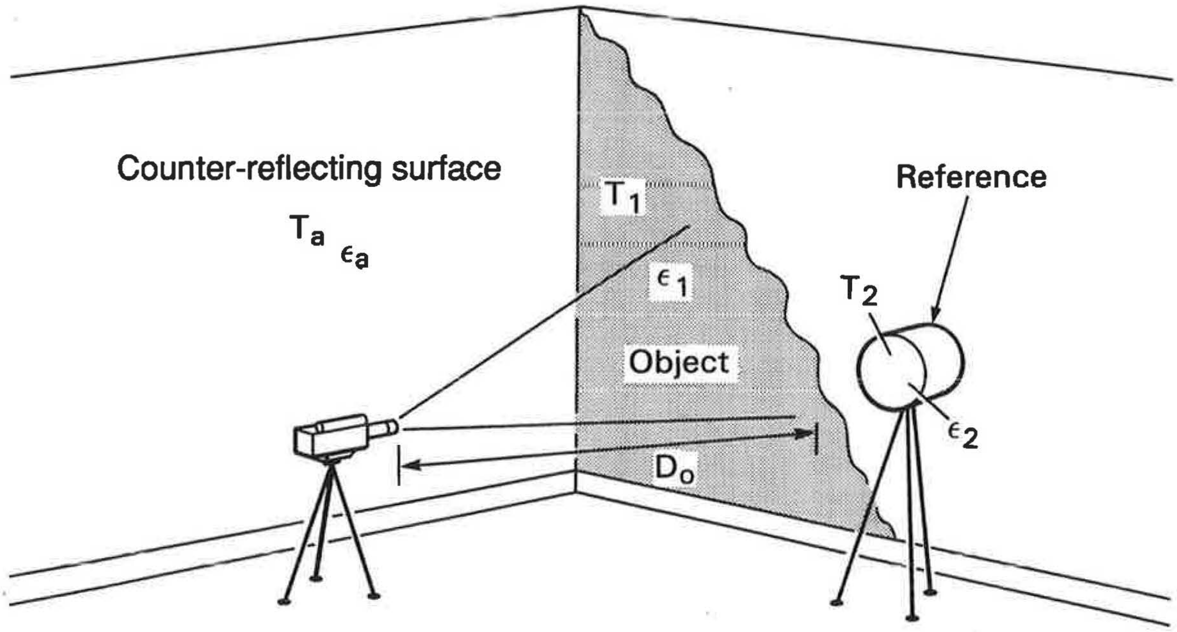
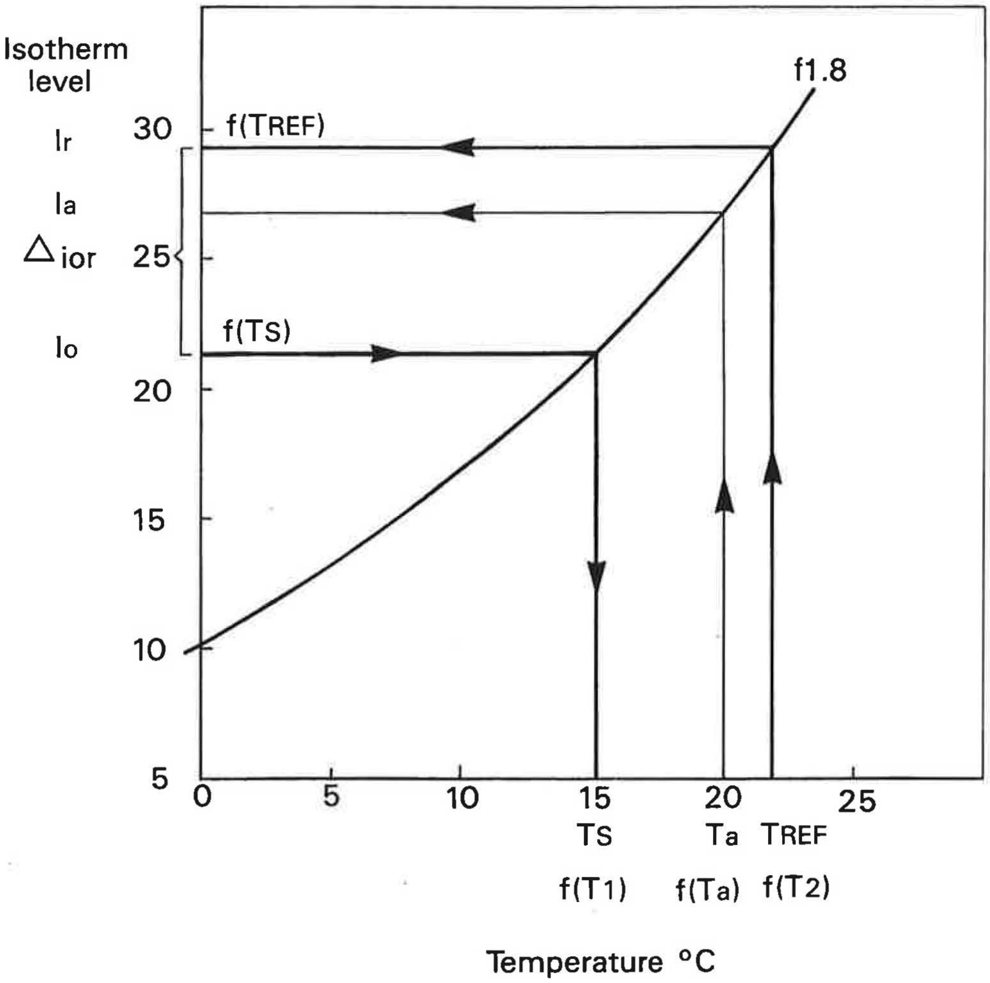


Figure A2.1 Temperature measurement with a reference source

Reference temp. 22°C = I_r = 29.5 isotherm units
Reference Emissivity ε_r = 1.0 isotherm units
Air temp. (T_a) = I_a = 27.5 isotherm units
Δ_{ior} = −7.5 isotherm units
Object Emissivity ε_r = 0.92 isotherm units



Example

$$I_o = \frac{\Delta_{ior}}{\varepsilon_o} + \frac{\varepsilon_r}{\varepsilon_o} I_r + \left(1 - \frac{\varepsilon_r}{\varepsilon_o}\right) I_a \qquad \text{(From A2 (1))}$$

$$I_o = \frac{-7.5}{0.92} + \frac{1.0}{0.92} \times 29.5 + \left((1 - \left(\frac{1.0}{0.92}\right)\right) \times 27.5$$

I_o = 21.5 isotherm units

From calibration curve:- 21.5 isotherm units = T_s = 15.0°C

Figure A2.2 Example calibration curve for AGA Thermovision System 782 (Aperture f1.8)

A2.2 Atmospheric influence on infra-red temperature measurement

The atmosphere is not completely transparent to infra-red radiation. Equation 14 assumed that all the radiation emitted from the surface of the object reached the detector in the infra-red camera. In practice, however, a certain amount is attenuated by the atmosphere between the object and the camera. The atmosphere will also emit radiation, this, however, can be ignored provided the object and reference are placed at the same distance from the camera.

The amount of signal attenuation due to the atmosphere is dependent on three main factors, they are:

1 The operational wavelength of the infra-red camera.
2 The subject to camera distance.
3 The composition of the atmosphere.

Figure A2.3 shows how atmospheric correction varies with object distance, for an infra-red camera operating in the wavelength region 3 to 5.6 μm and assuming a standard atmosphere (defined in Table A2.1).

For the majority of internal thermography applications in buildings, the effect of atmospheric absorption, for camera to object distances under 5 m, is quite small and can often be disregarded.

TABLE A2.1 Factors Influencing the Atmospheric Correction Factor τ

Parameter	Standard atmosphere
Scanner type SW (3 to 5.6 µm)	
Scanner to object distance m	
Air temperature	15°C
Air pressure	latm. = 1013 mb
Relative humidity (RH%)	50%
Carbon dioxide (CO_2)	300 ppm
Carbon monoxide (CO)	1 ppm
Nitrous oxide (N_2))	0.3 ppm
Ozone (O_3)	0.355 ppm
Methane (CH_4)	2 ppm
Aerosol visibility (particles)	10 km

The atmospheric correction factor is given by: $\tau = \exp(-\alpha(D_o^{0.5}-1))$

where τ is the correction factor

α is the attenuation coefficient = 0.046 for the short wavelength scanner (3 to 5.6 μm)

D_o is the distance from the scanner to the object and reference

Do (Meters)	τ atm
1	1
2	0.98
5	0.94
10	0.91
20	0.85
50	0.76
100	0.66
200	0.55
500	0.37

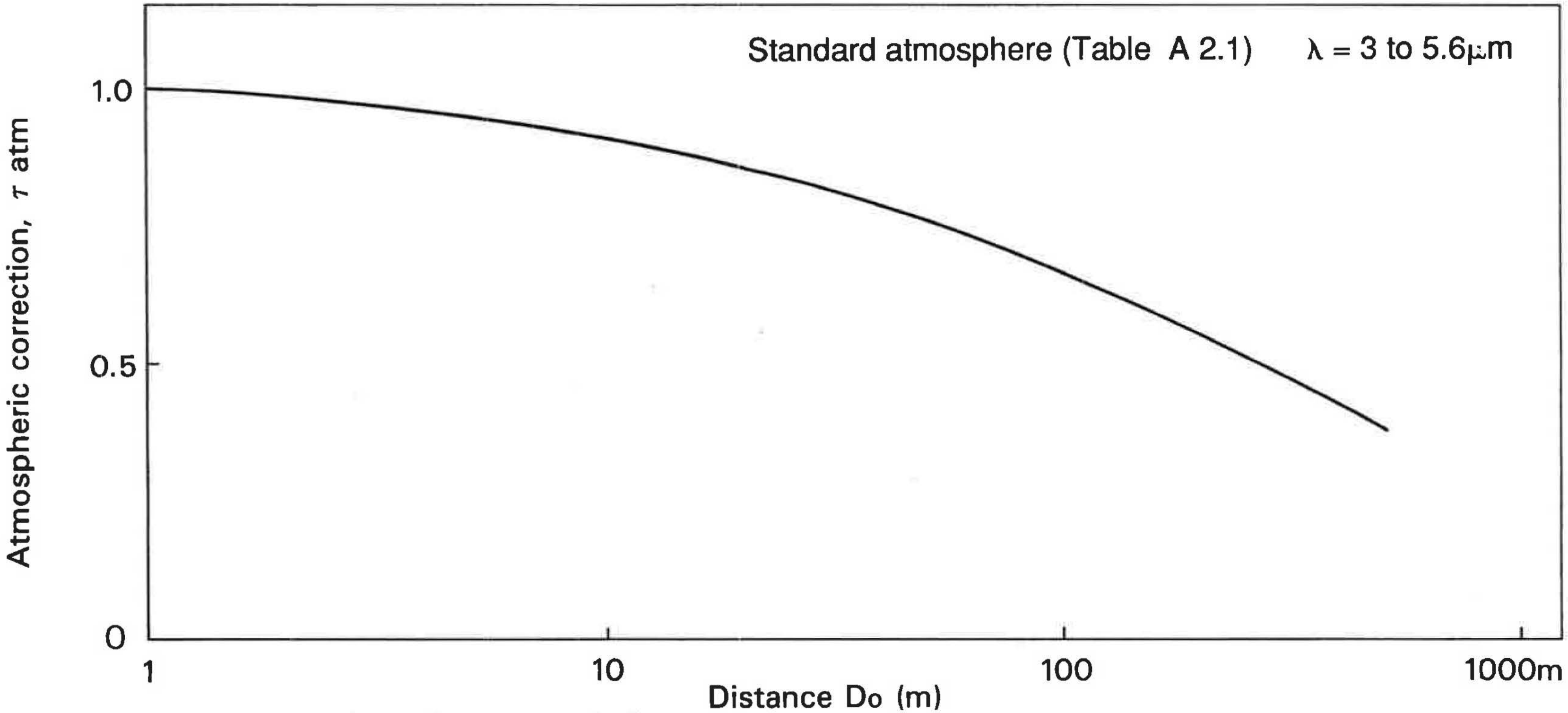


Figure A2.3 Correction factors for atmospheric attenuation τ_{atm} as a function of camera to object distance for short wavelength cameras (3 to 5.6 μm)

A2.3 Practical thermographic interpretation

In Section **A2.1** the basic formula for thermal measurement using an infra-red camera and known reference temperature was derived (Equation 14).

In practice a number of simplified formulae may be used for absolute temperature measurement depending upon the known parameters. All, however, involve the infrared cameras calibration curves and a combination of the parameters listed below:-

T_o = Object temperature °C

ε_o = Object emissivity

T_r = Reference temperature °C

ε_r = Reference emissivity

T_a = Ambient air temperature °C

D_o = Camera to object distance m

Δ_{ior} = Difference in isotherm units between the isotherm markers on the grey scale for the object and reference points on the thermal image ($i_o - i_r$).

I_o = Absolute isotherm level for the object temperature, T_o read from the calibration charts

I_r = Absolute isotherm level for the reference temperature, T_r read from the calibration charts

I_a = Absolute isotherm level for the ambient air temperature, T_a read from the calibration charts

Note:-

The image isotherm levels i_o and i_r are obtained by multiplying the isotherm marker positions for the object and reference temperatures, respectively, by the SENSITIVITY setting in use at the time. The sign for Δ_{ior} can be either positive or negative depending upon the relative positions of the object and reference isotherms.

A2.4 Practical formulae

(i) When both object temperature and reference emissivity can vary.

Basic formula for determining isotherm value I_o for the true temperature of objects when ε_o, T_r, ε_r, T_a and D_o are known:-

$$I_o = \frac{\Delta_{ior}}{\varepsilon_o\tau_o} + \frac{\tau_r\varepsilon_r}{\tau_o\varepsilon_o} I_r + (1 - \frac{\tau_r\varepsilon_r}{\tau_o\varepsilon_o}) I_a \qquad \text{Equation 15}$$

Re-arranging the above for object emissivity, ε_o when T_o, T_r, ε_r, T_a and D_o are known:-

$$\varepsilon_o = \frac{\Delta_{ior} + \tau_r\varepsilon_r (I_r - I_a)}{\tau_o (I_o - I_a)} \qquad \text{Equation 16}$$

(ii) When the reference temperature source is a blackbody simulator ($\varepsilon_r = 1$)

Formula for determining I_o when ε_o, T_r, T_a and D_o are known:-

$$I_o = \frac{\Delta_{ior}}{\varepsilon_o\tau_o} + \frac{\tau_r I_r}{\tau_o\varepsilon_o} + (1 - \frac{\tau_r}{\tau_o\varepsilon_o}) I_a \qquad \text{Equation 17}$$

Rearranging for ε_o when T_o, T_r, T_a and D_o are known:-

$$\varepsilon_o = \frac{\Delta_{ior} + \tau_r (I_r - I_a)}{\tau_o (I_o - I_a)} \qquad \text{Equation 18}$$

(iii) When the difference in temperature between two points on the same object is measured ($\varepsilon_r = \varepsilon_o$).

Formula for determining I_o when ε_o, T_r, and D_o are known:-

$$I_o = \frac{\Delta_{ior}}{\tau_o \varepsilon_o} + I_r \qquad \textbf{Equation (19)}$$

Rearranging for ε_o when T_o, T_r and D_o are known:-

$$\varepsilon_o = \frac{\Delta_{ior}}{\tau_o (I_o - I_r)} \qquad \textbf{Equation (20)}$$

Note: The correction factor for atmospheric attenuation (τ_o) has been applied to the above formulae where appropriate. From Figure A2.3 the value of τ_{atm} can be read against distance in metres, (D_o). All the above formulae assume both object and reference are at the same distance from the camera.

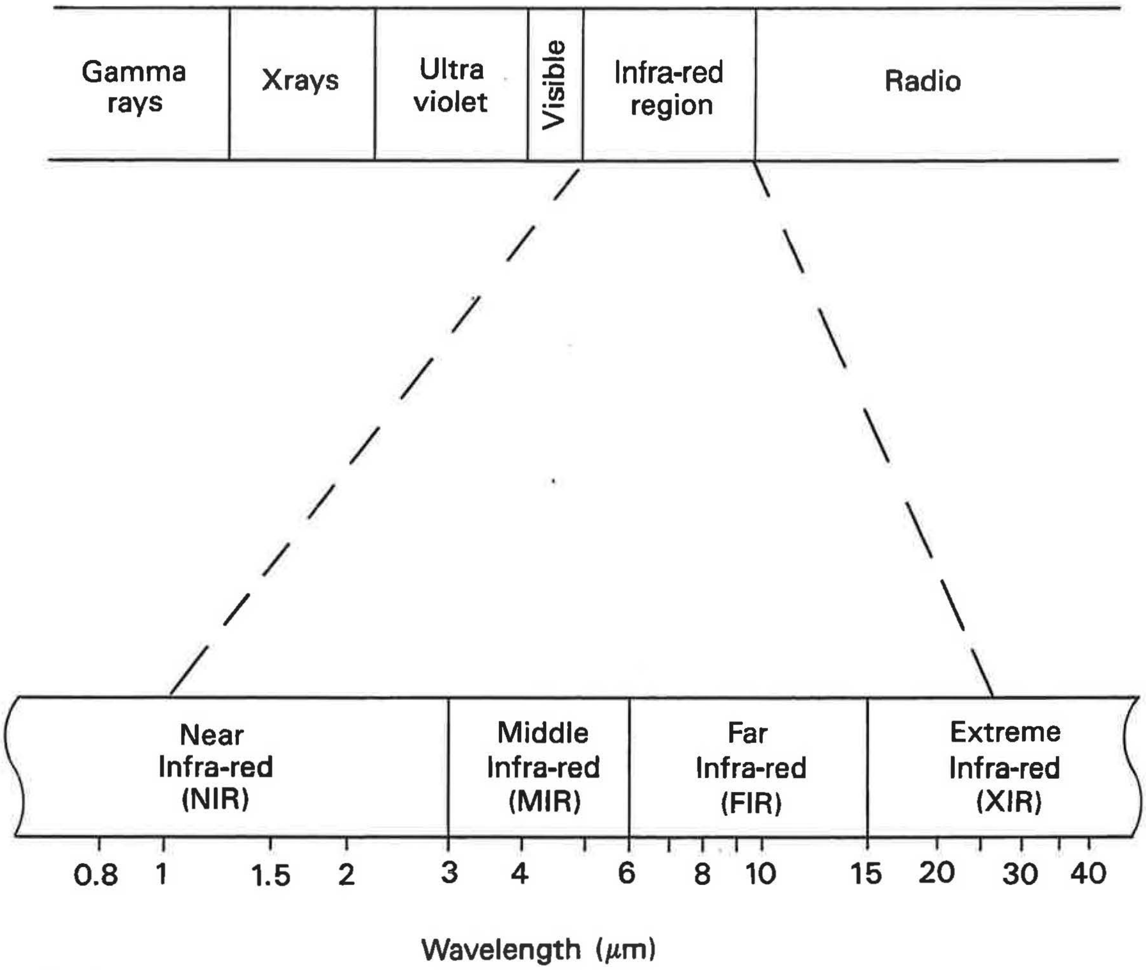
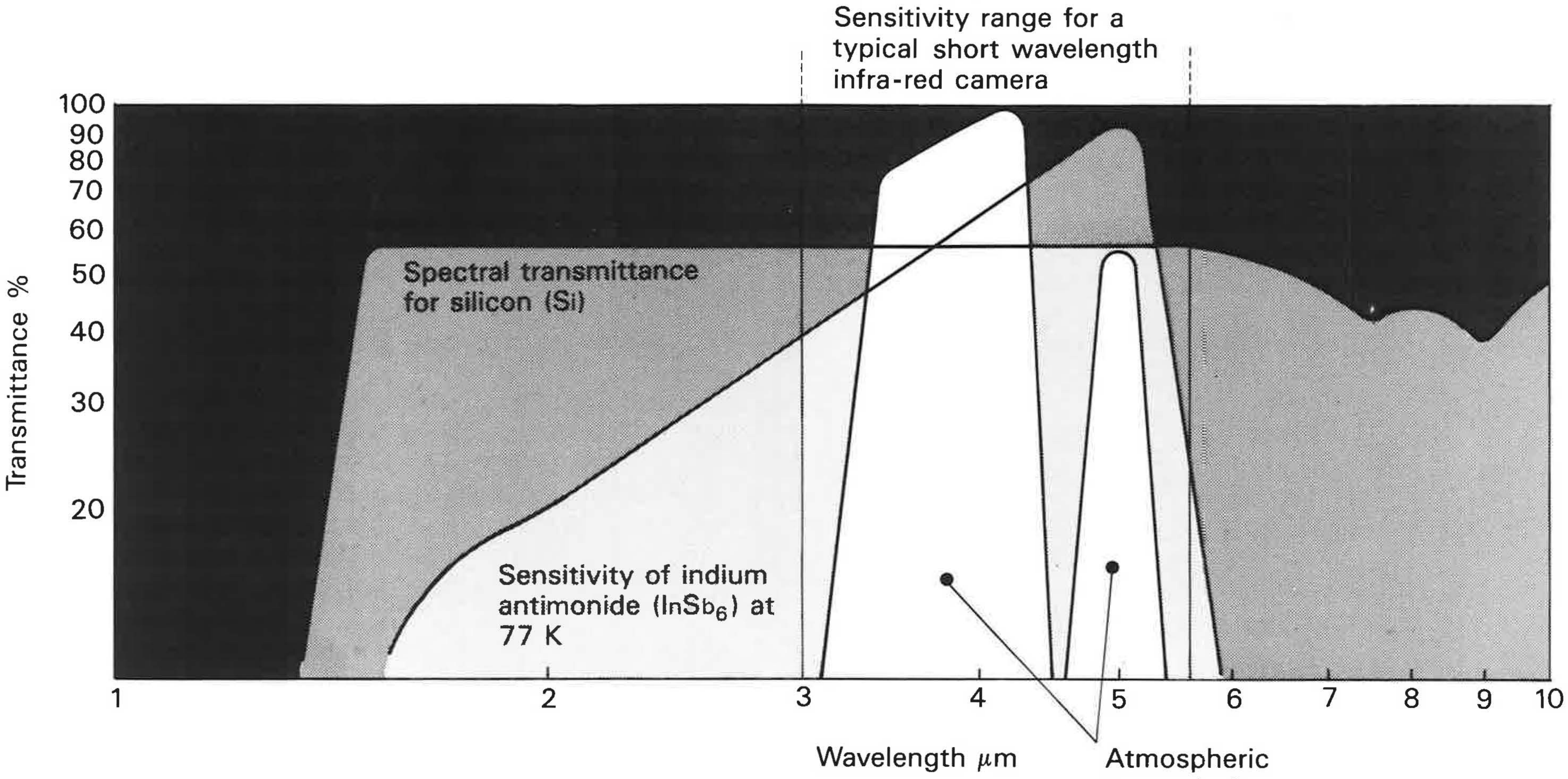


Figure 1 The electromagnetic spectrum

Figure 2 Thermovision 782 portable infra-red equipment



The wavelength dependant sensitivity of $InSb_6$ as a radiation detector coupled with silicon optics give the short wavelength infra-red camera a working wavelength band of 3 to 5.6 μm. The atmospheric 'window' in this wavelength band is also shown.

Figure 3 Camera operating wavelength range

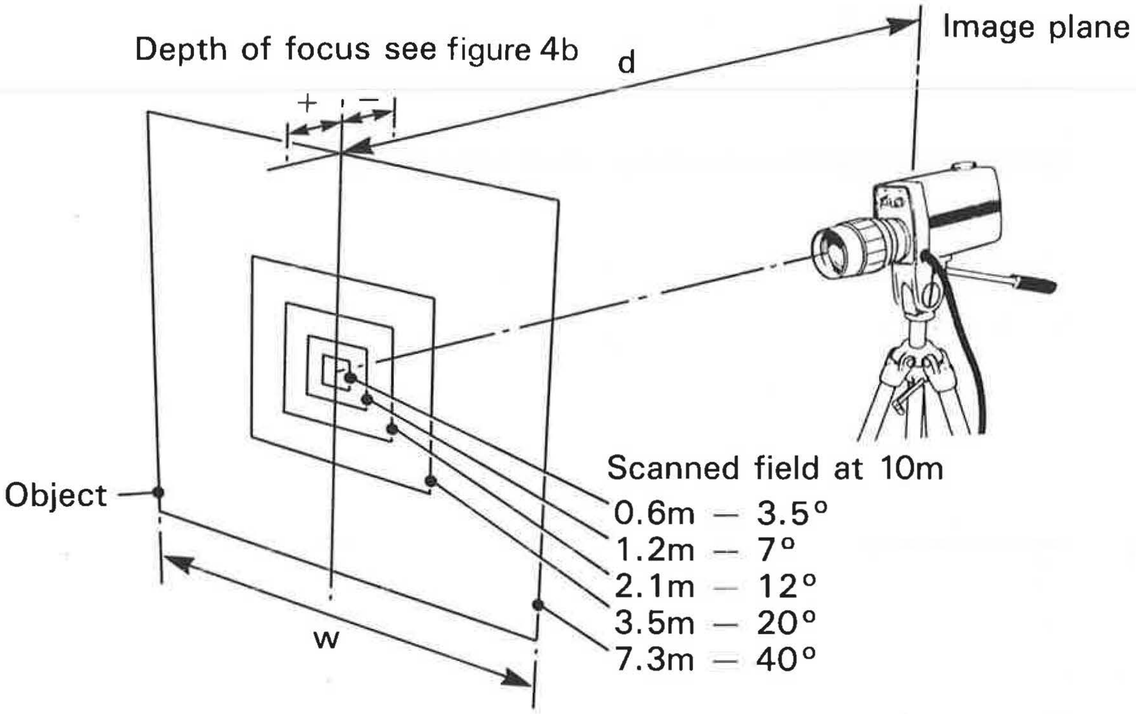


Figure 4(a) Field of view and depth of focus -- measurement

		Object to image plane distance (d) metres							
Lens		**0.2**	**0.5**	**0.7**	**1**	**2**	**3**	**5**	**10**
3.5° × 3.5°	w						0.16	0.28	0.59
	+						0.09	0.28	1.3
	−						0.08	0.25	1.0
7° × 7°	w				0.10	0.22	0.34	0.59	1.2
	+				0.06	0.22	0.48	1.2	5.5
	−				0.03	0.17	0.36	0.9	2.8
12° × 12°	w			0.12	0.19	0.42	0.65	1.1	2.1
	+			0.05	0.13	0.80	2.4	20.7	
	−			0.04	0.10	0.43	0.90	2.2	6.2
20° × 20°	w		0.15	0.22	0.33	0.68	1.0	1.7	3.5
	+		0.08	0.28	0.68	8.5			
	−		0.08	0.15	0.29	0.90	1.6	3.3	8.0
40° × 40°	w	0.10	0.31	0.46	0.67	1.4	2.1	3.5	7.3
	+	0.04	0.80	9.3					
	−	0.17	0.17	0.31	0.55	1.4	2.4	4.3	9.3

NOTE: All measurements are in metres.

Figure 4(b) Scanned field (w) and depth of focus (+/−) set at various object to image plane distances.

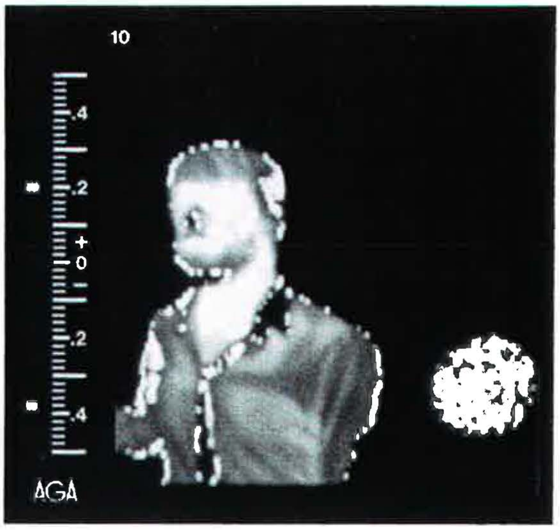


Figure 5 A thermogram of the author with isotherm markers

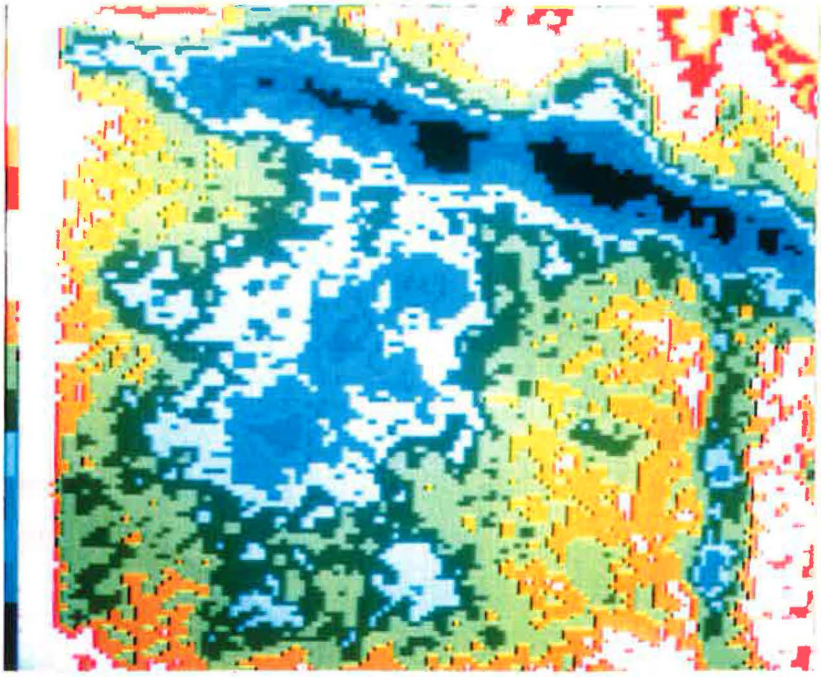


Figure 6 A qualitative thermogram showing patches of missing insulation (black) spreading down from a 'cold' wall to ceiling joint

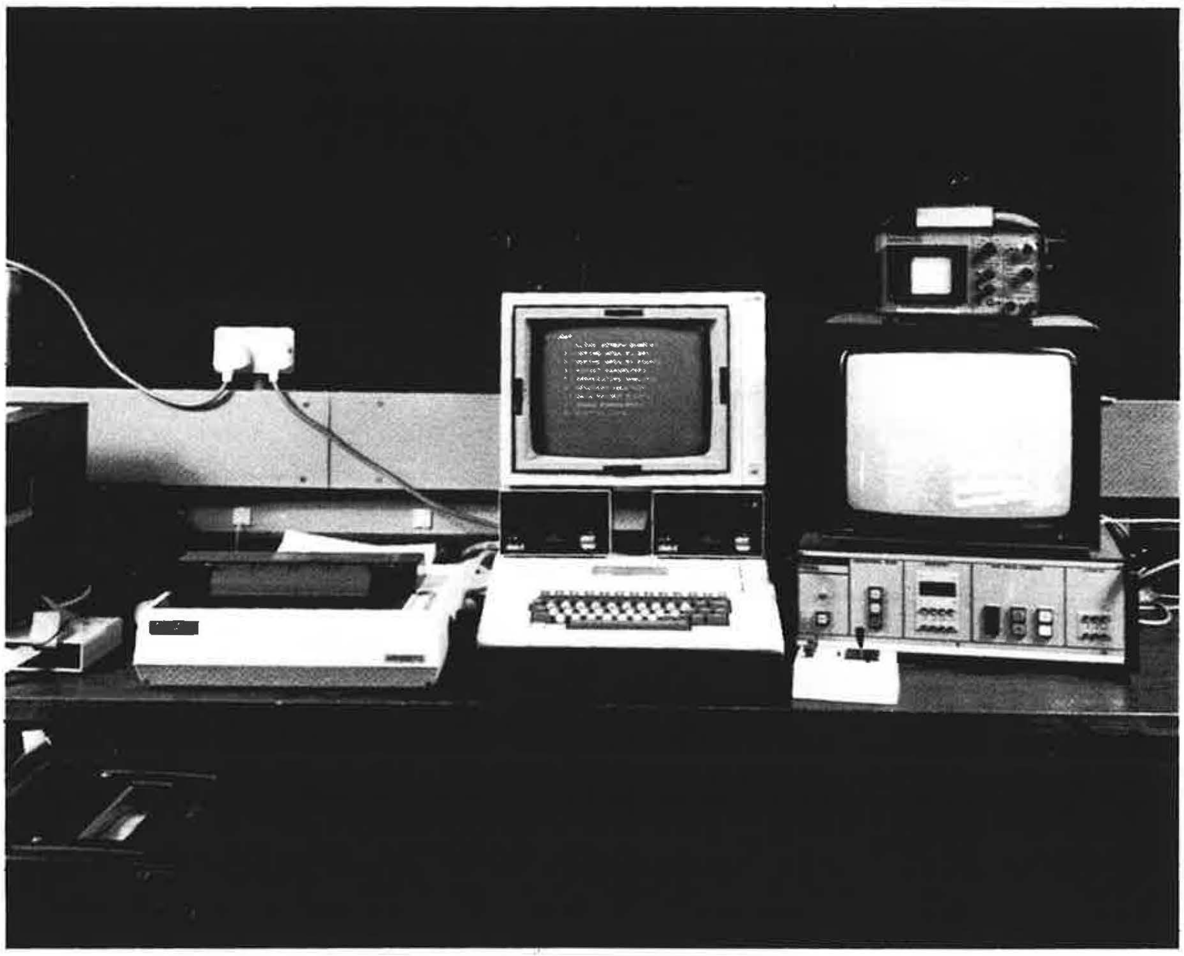
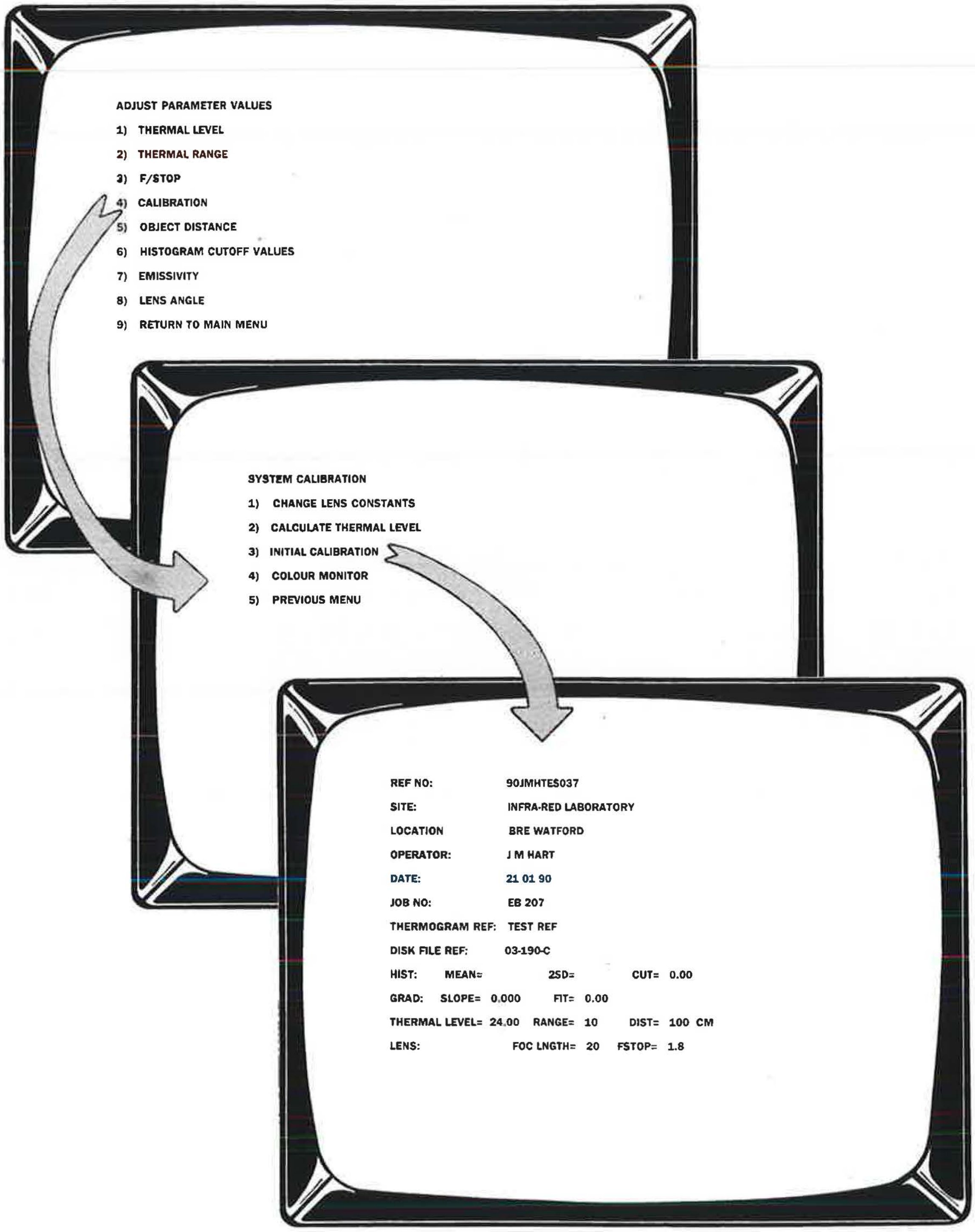
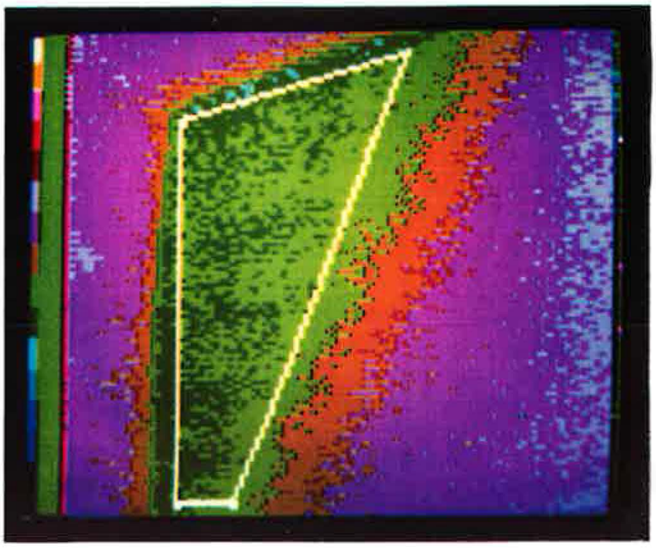


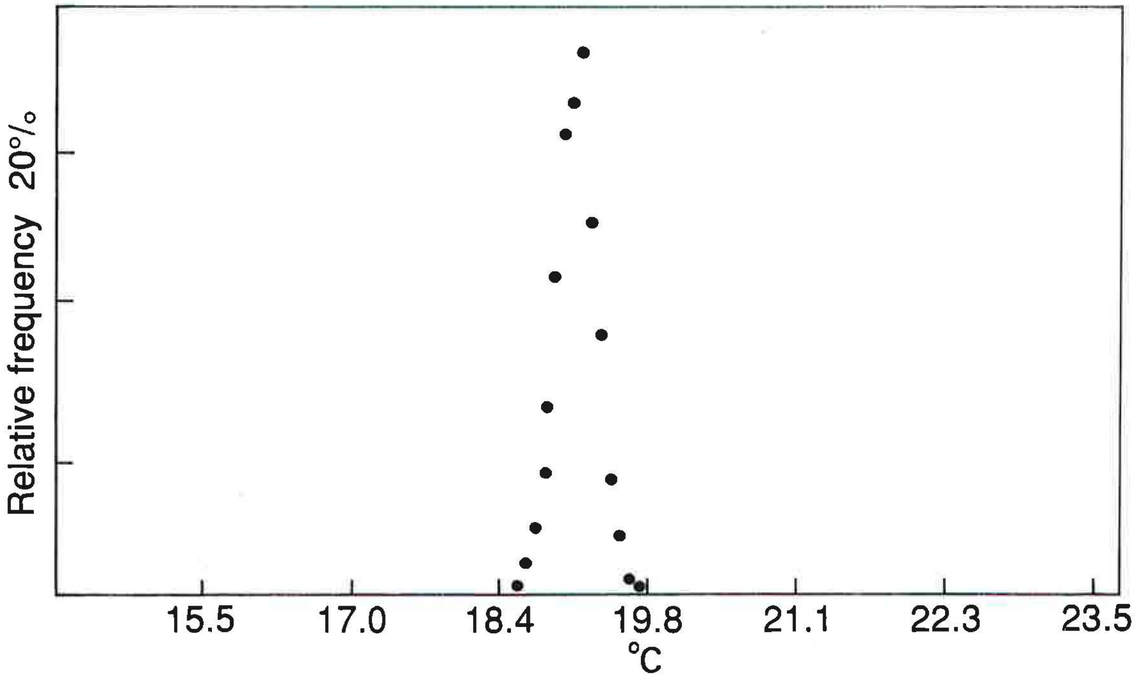
Figure 7 The thermal image processor



```
REF NO:            90JMHTES037
SITE:              INFRA-RED LABORATORY
LOCATION           BRE WATFORD
OPERATOR:          J M HART
DATE:              21 01 90
JOB NO:            EB 207
THERMOGRAM REF:    TEST REF
DISK FILE REF:     03-190-C
HIST:      MEAN=             2SD=             CUT=  0.00
GRAD:     SLOPE=  0.000      FIT=  0.00
THERMAL LEVEL=  24.00   RANGE=  10          DIST=  100  CM
LENS:                    FOC LNGTH=  20    FSTOP=  1.8
```

Figure 8 Thermal analysis - example of data input and record filing of the computer based thermal image processor





Peak = 18.7 % at 19.2
Mean = 19.1 deg, SD = 0.18
2426 pixels enclosed

The highlighted boundary marks the area in which the computer has to calculate the maximum and minimum temperature together with the mean surface temperature. It will also produce a pixel frequency plot (below) showing the temperature distribution.

Figure 9 Thermal analysis — example of result output

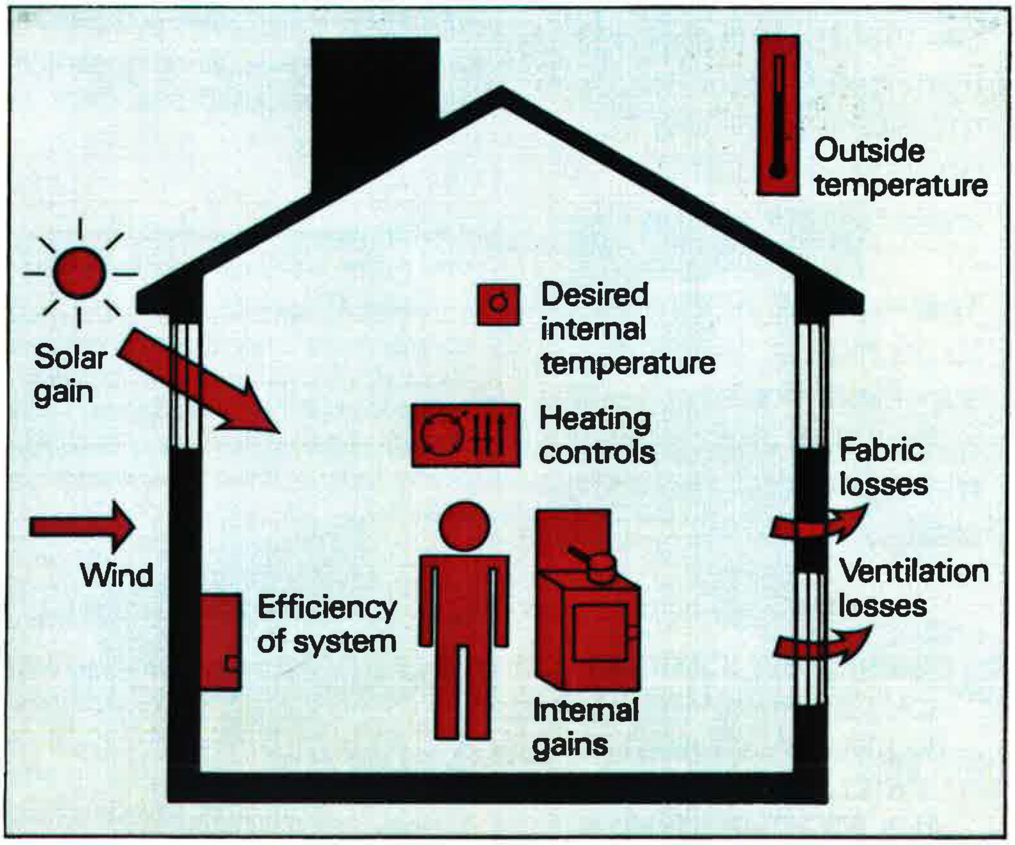


Figure 10 Heat loss paths from a building

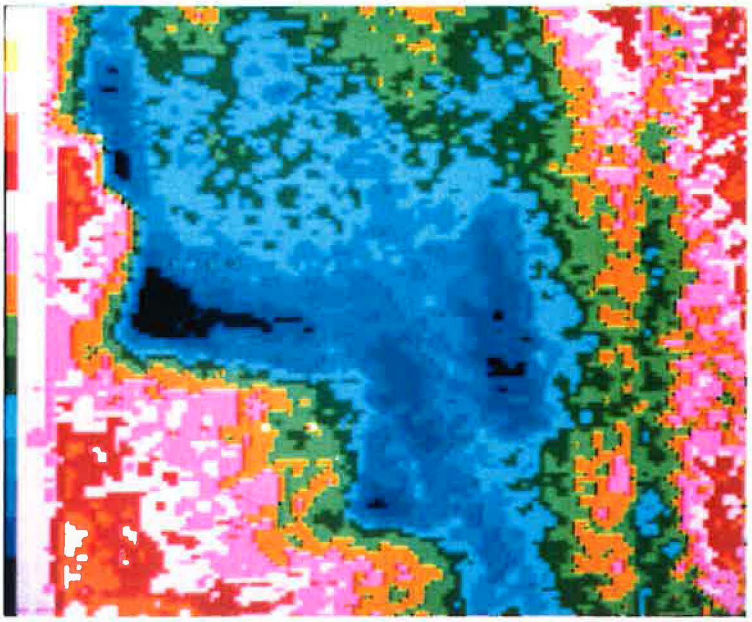


Figure 11 Thermogram - variations in surface temperature

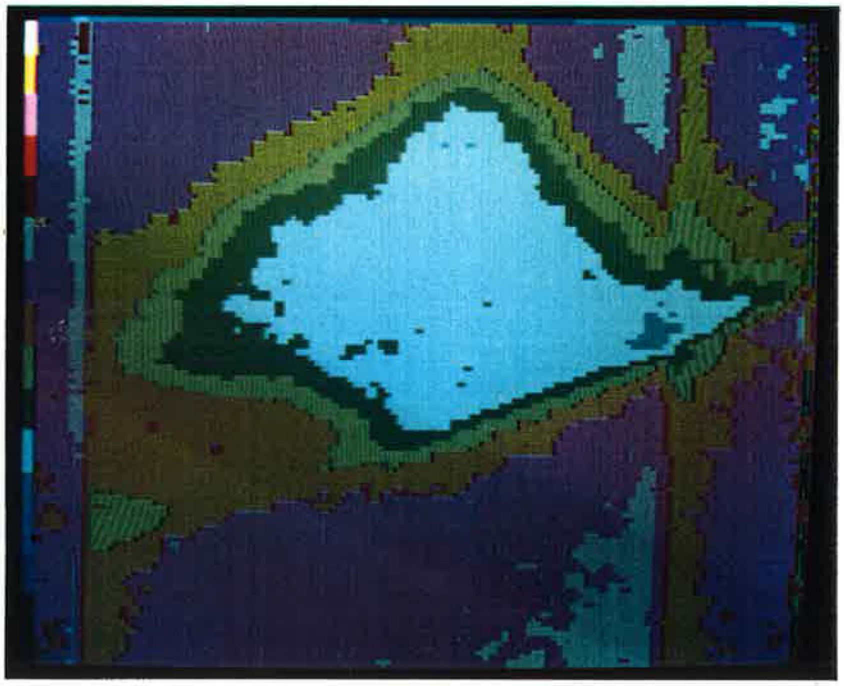


Figure 12 Thermogram - cold area on a ceiling

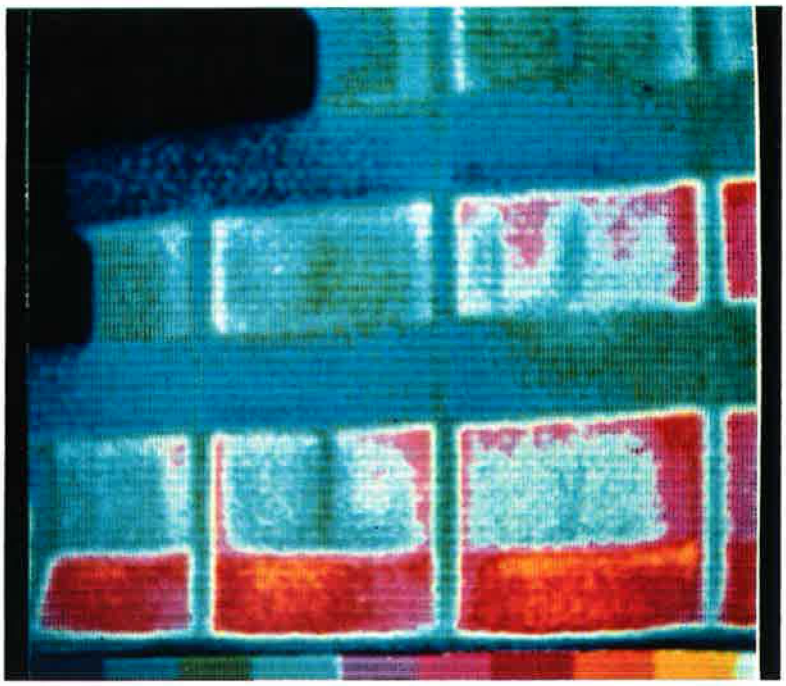


Figure 13 Thermogram - historic influence of solar radiation on external surfaces

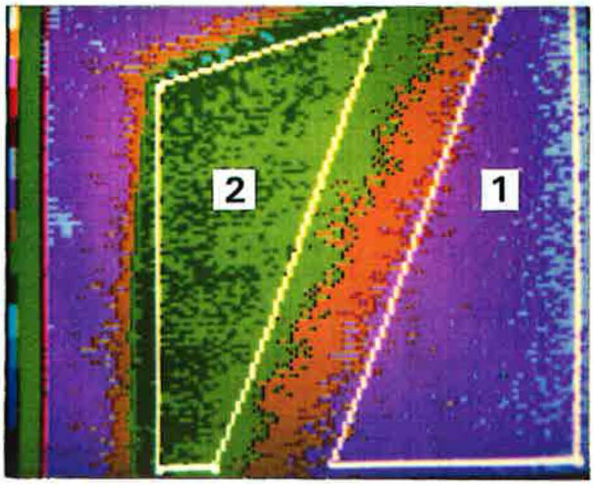


Figure 14 Thermogram - quantified in terms of surface temperatures Area 2 on the left hand side has a surface temperature 1.6°C lower than the rest of the insulated wall. Peak white defines the analysis areas.

Analytical parameters:

Reference temperature	22.0°C
Reference emissivity	1.0
Object emissivity	0.92
Camera to object distance	2.0m
External air temperature	4.0°C
Camera aperture setting	f1.8
Camera thermal range	5.0

Calculated surface temperature:

For defined area 1 = 20.7°C
For defined area 2 = 19.1°C

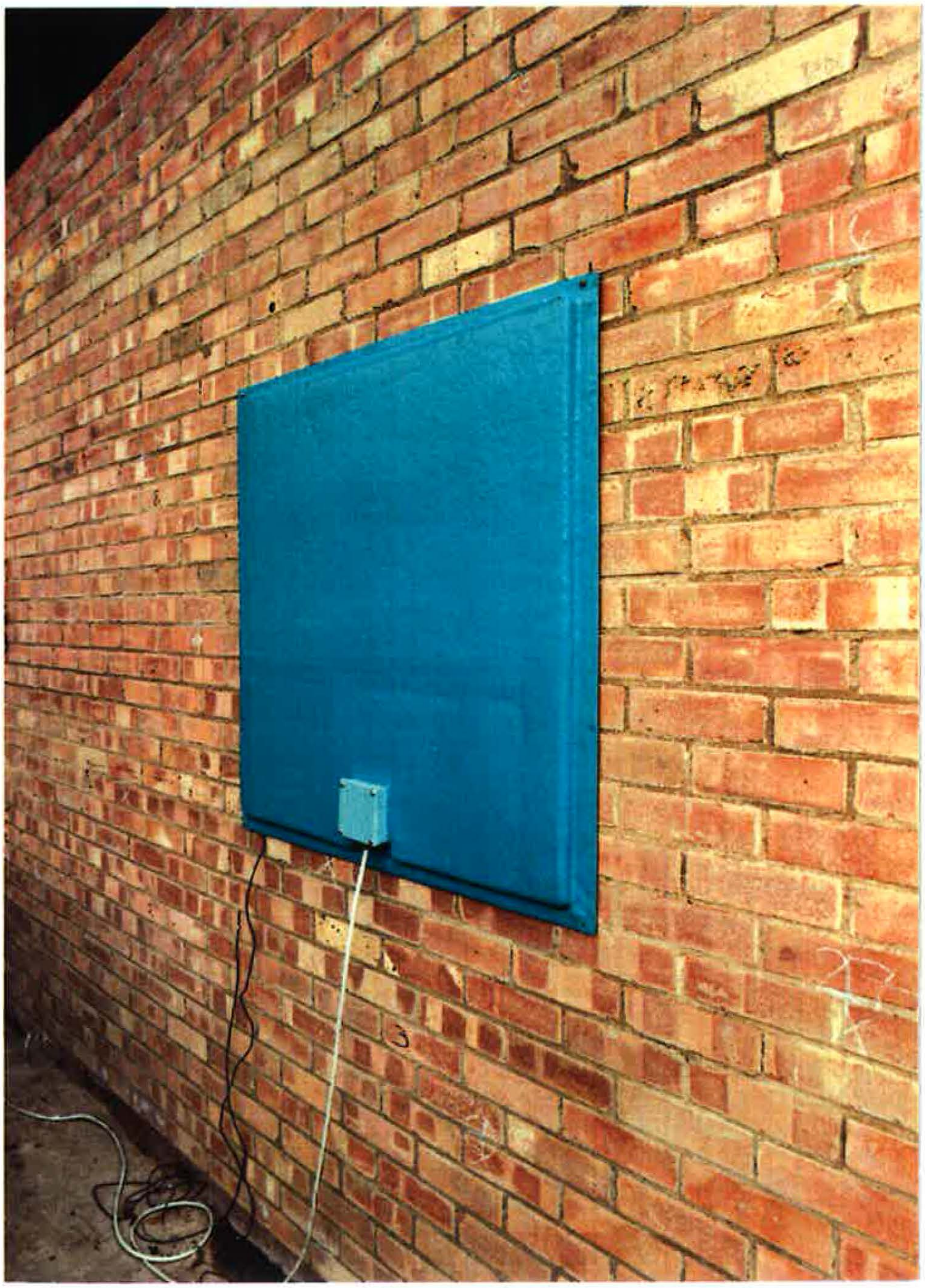


Figure 15 Application of local heating of surfaces

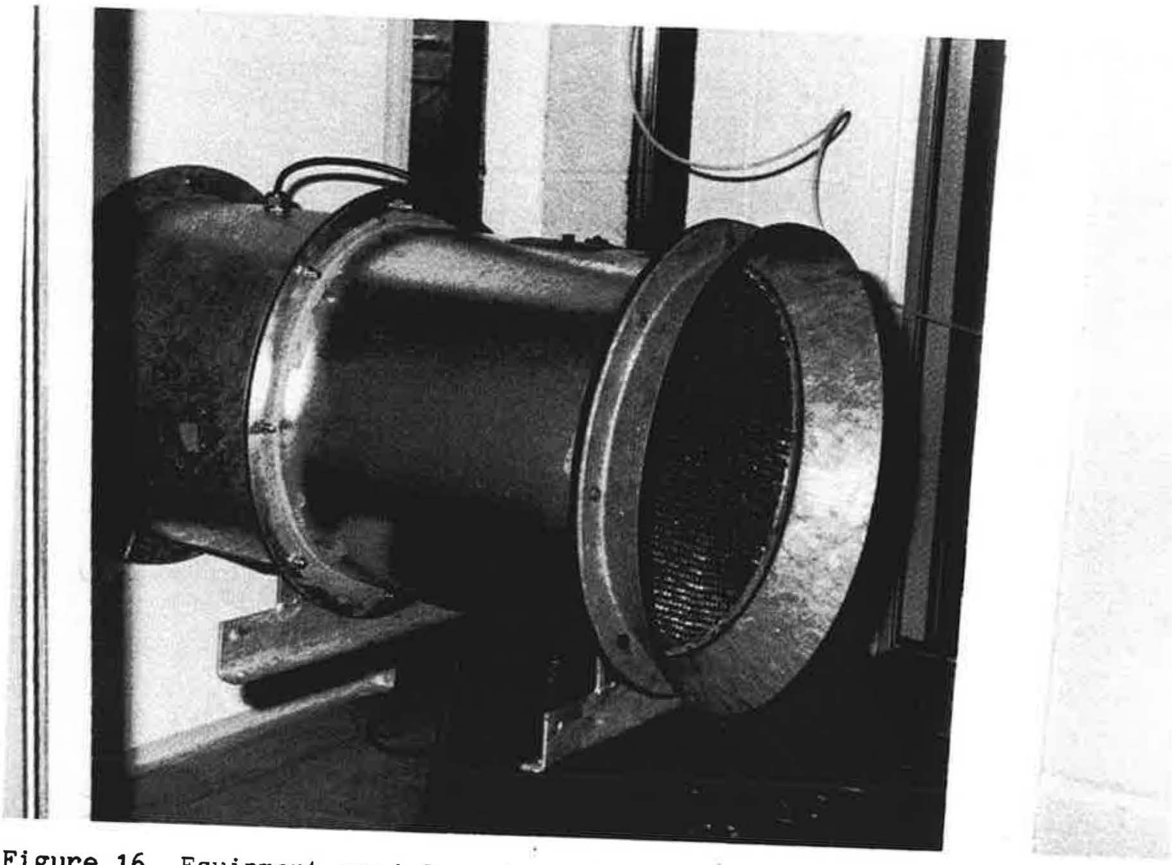


Figure 16 Equipment used for air leakage testing

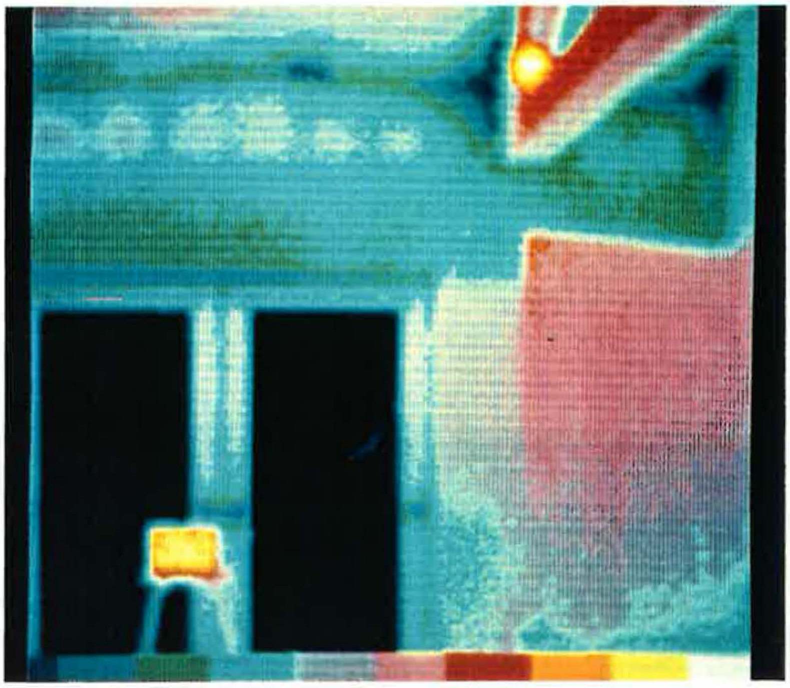


Figure 17(a) Air leakage path at a wall to ceiling joint

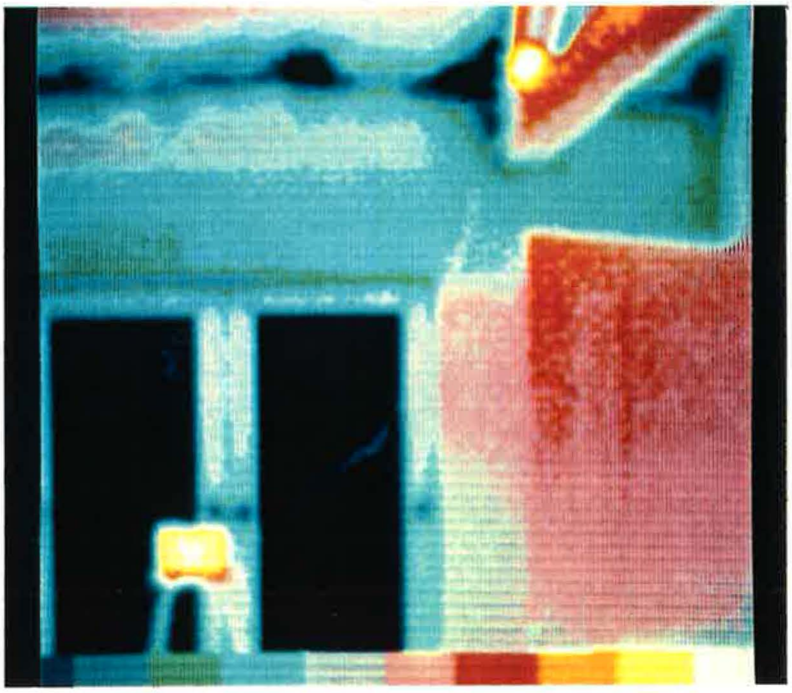


Figure 17(b) As 17(a) but 10 mins later with a pressure difference of 45 Pa across the building

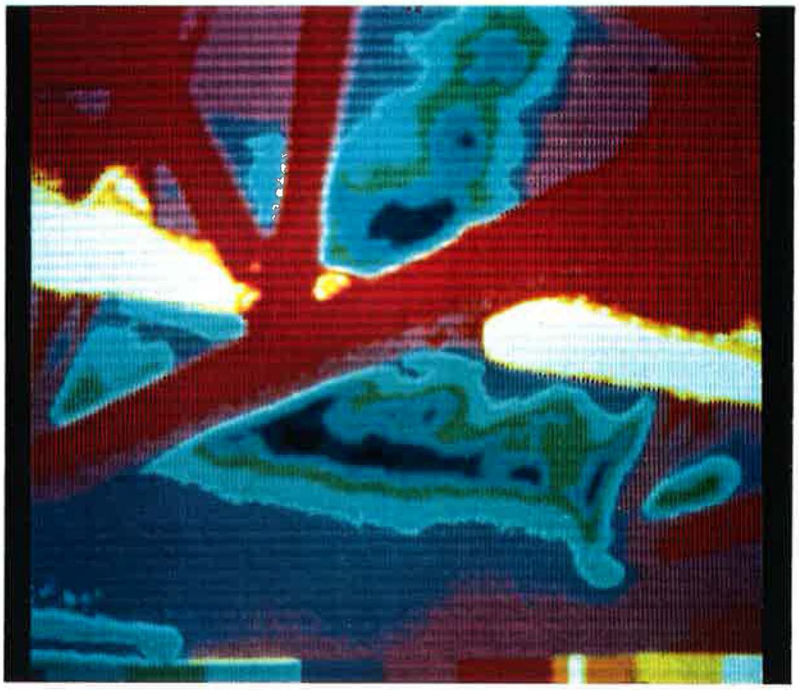


Figure 18 Internal surface cooled by the increased ingress of cold external air

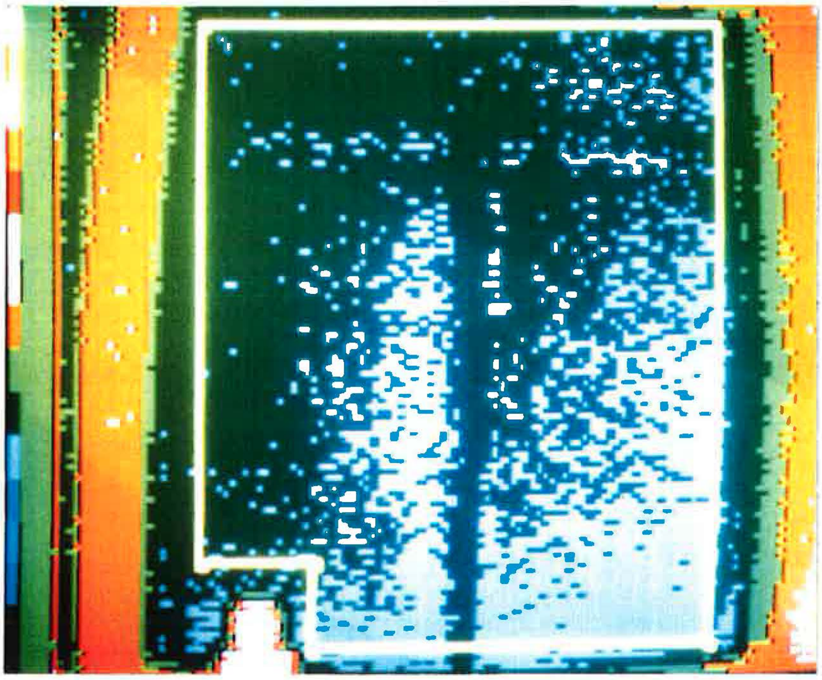


Figure 19 Thermogram of a single glazed metal framed window

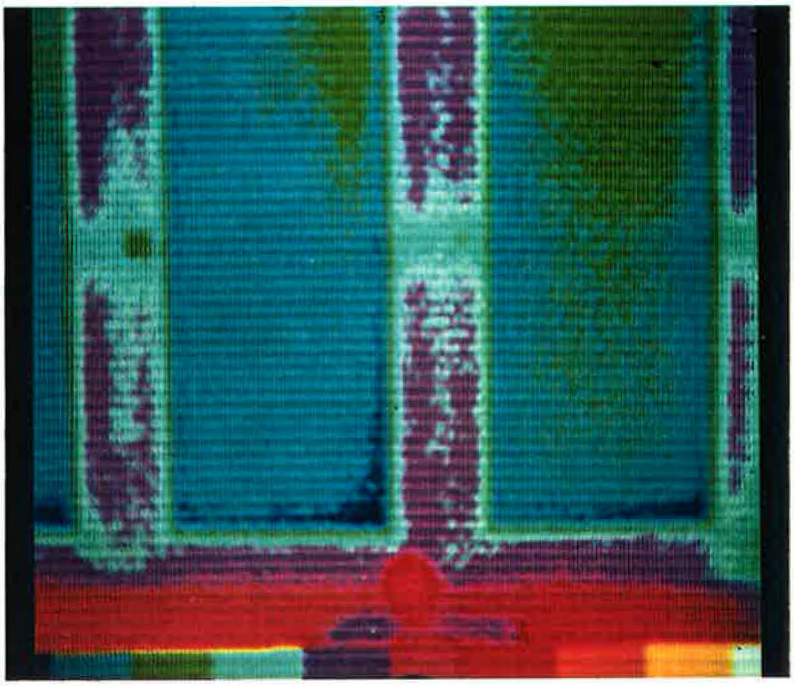


Figure 20(a) Thermogram of double glazed wooden framed window (glass temp)

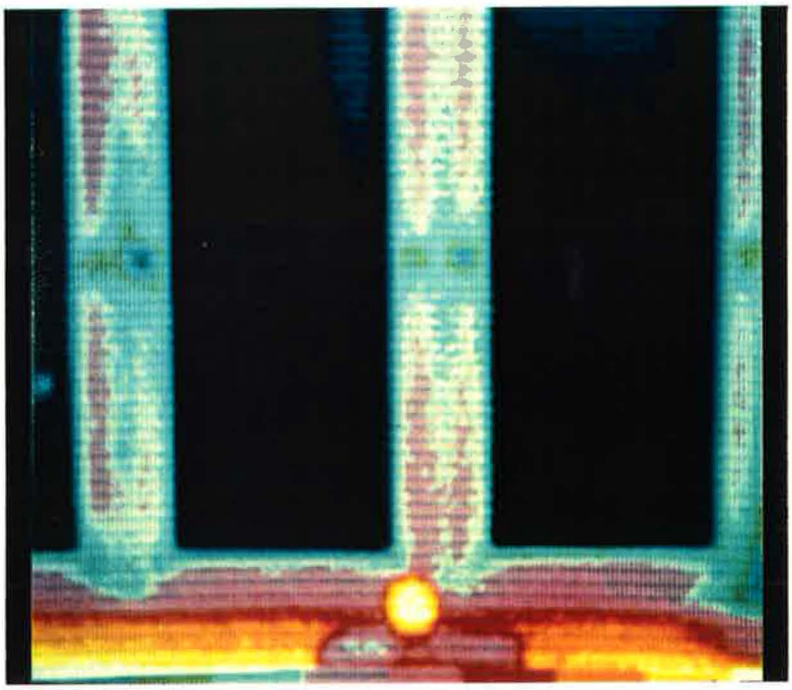
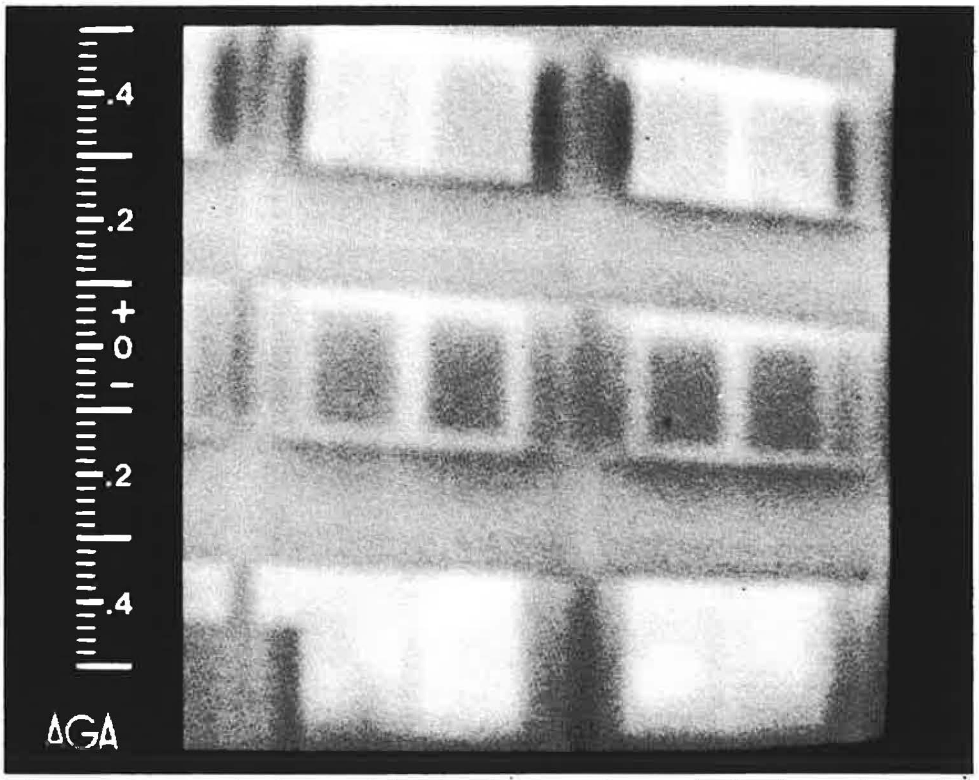
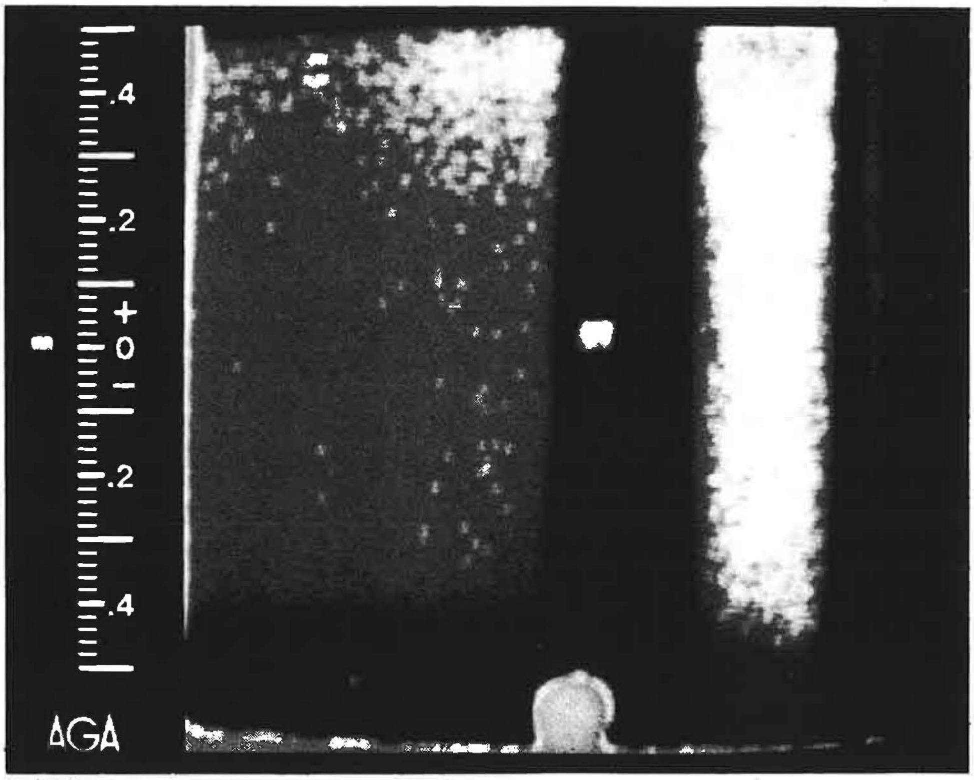


Figure 20(b) As 20(a) showing frame temperature



The centre windows block shows the relatively colder low 'e' glass.

Figure 21(a) Comparison of conventional and low 'e' glazing. External thermogram showing the relatively colder surface of low 'e' glass (centre windows-block)



Argon filling is absent in the left hand window

Figure 21(b) Faulty argon filled low 'e' glazing
Left hand window reveals absent argon fill on this low 'e' glazing unit. Smaller right hand window has argon and isotherm marker

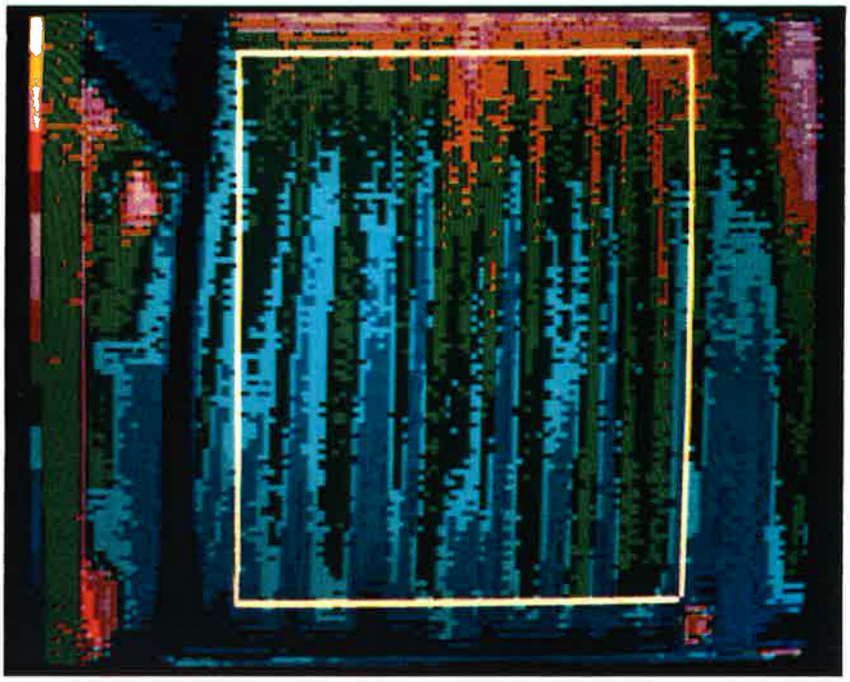


Figure 22 Thermogram of a window with unlined curtains

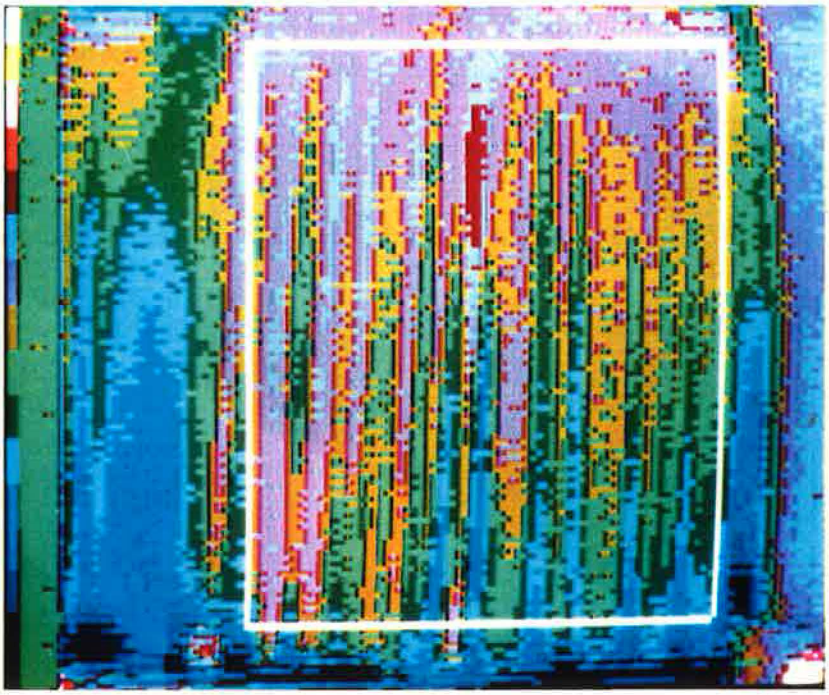


Figure 23 As Figure 22 but with the addition of loose linings

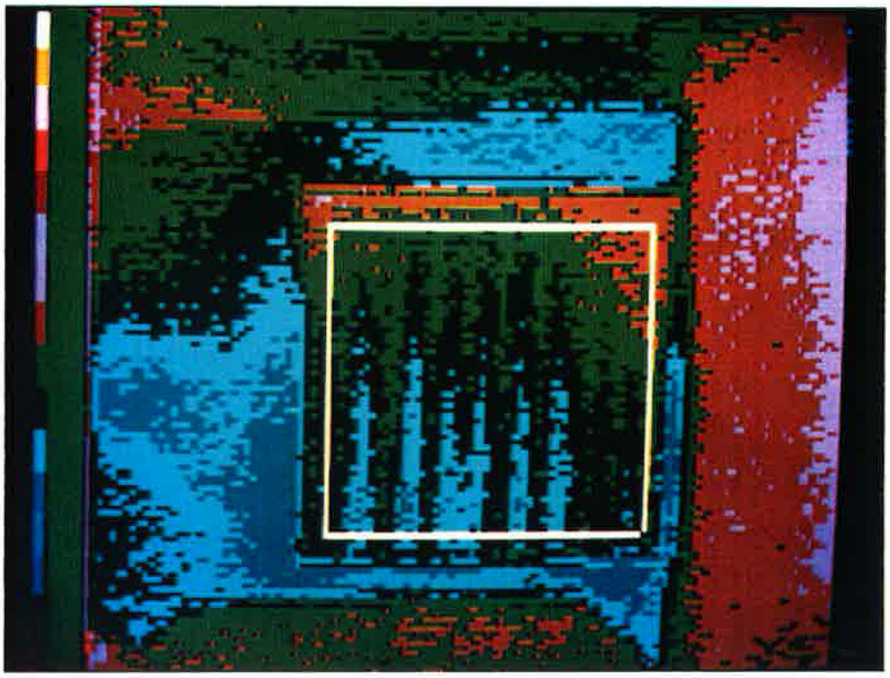


Figure 24 Surface temperature of a single glazed window without a radiator beneath

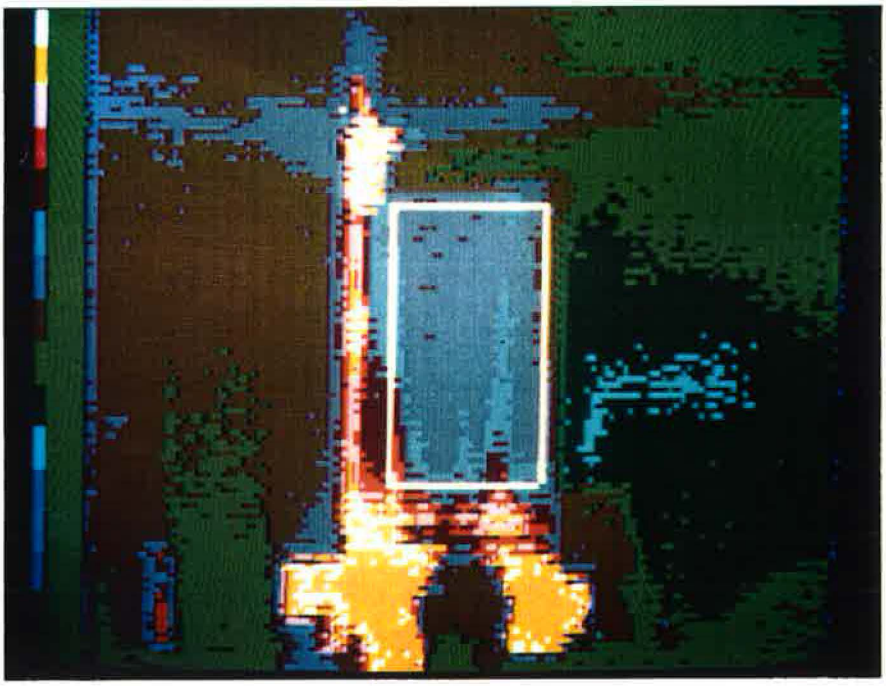


Figure 25 As Figure 24 but with a radiator beneath

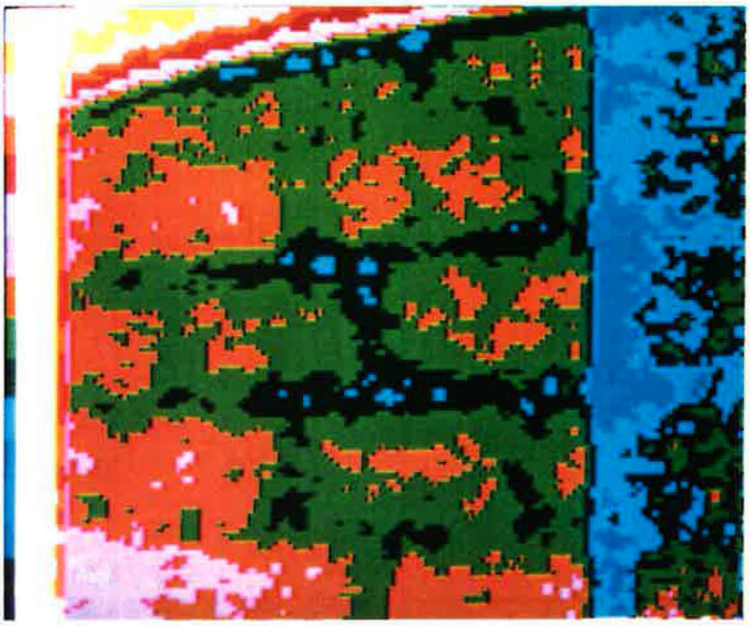


Figure 26 Thermogram showing 'hidden detail' - perpends behind plaster

Figure 27 Application of thermography to wall tie detection

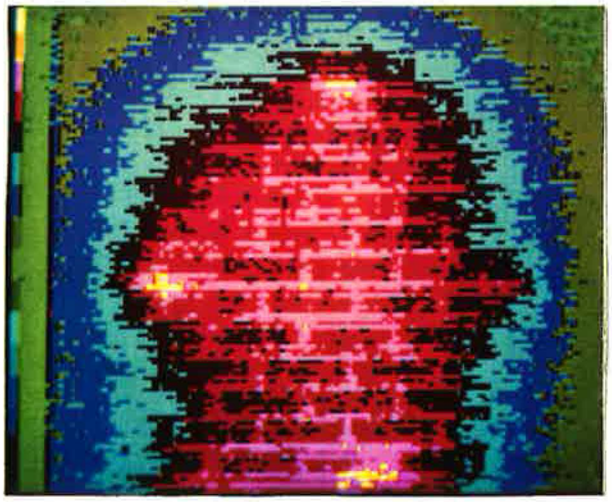


Figure 28 Thermogram showing position of detected wall ties

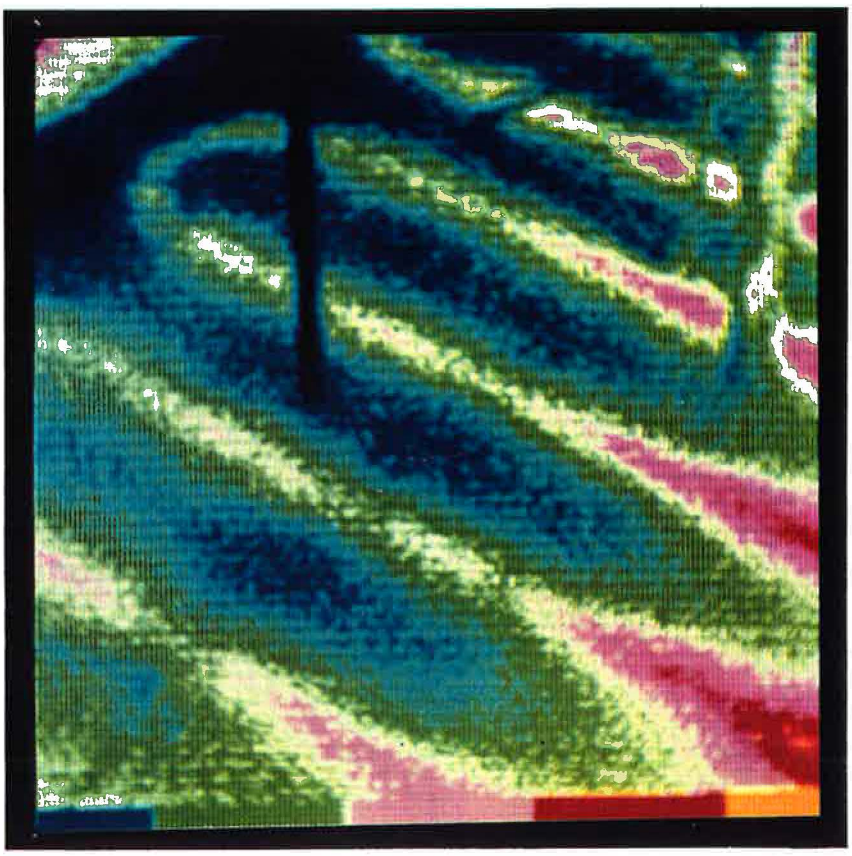


Figure 29(a) Underfloor heating pipes on a ground floor installation

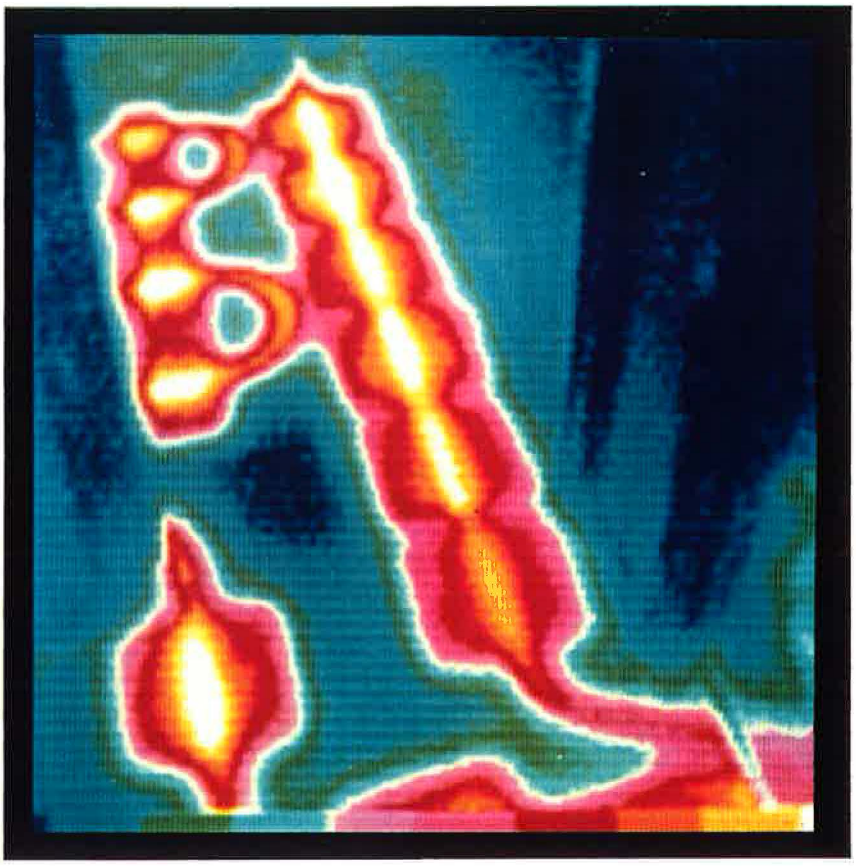


Figure 29(b) As Figure 29(a) but first floor installation showing heat spreader plates

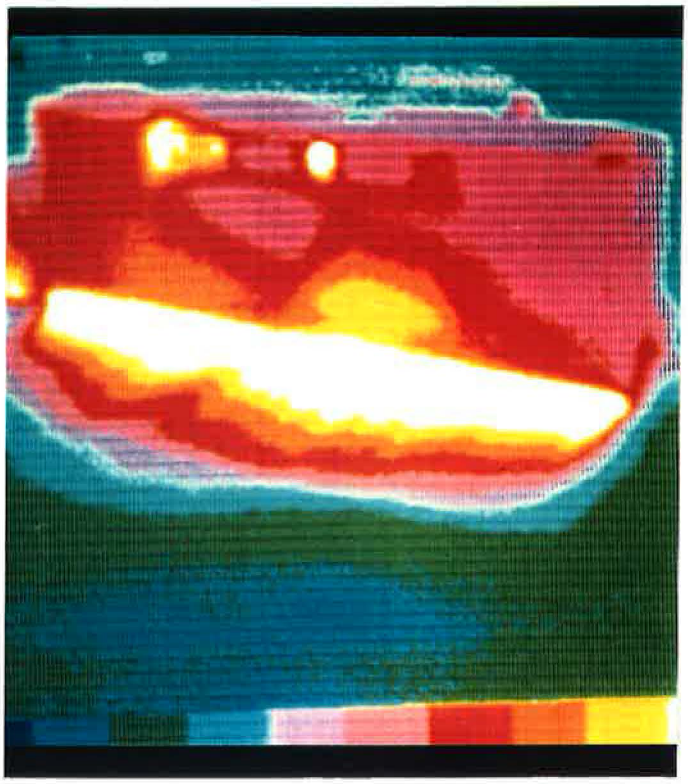


Figure 30(a) Heat distribution from a convector/blower heater

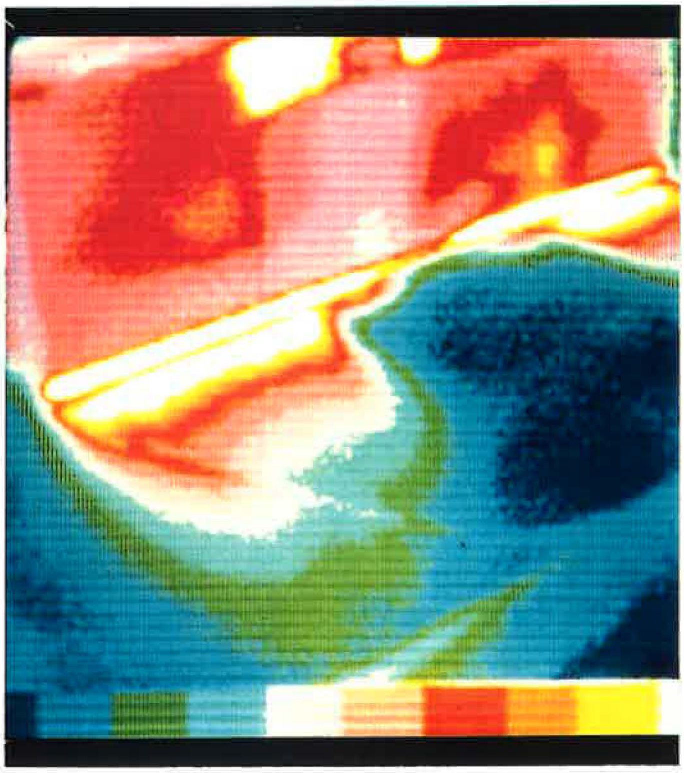


Figure 30(b) As Figure 30(a) but showing a heater with a semi-blocked outlet register

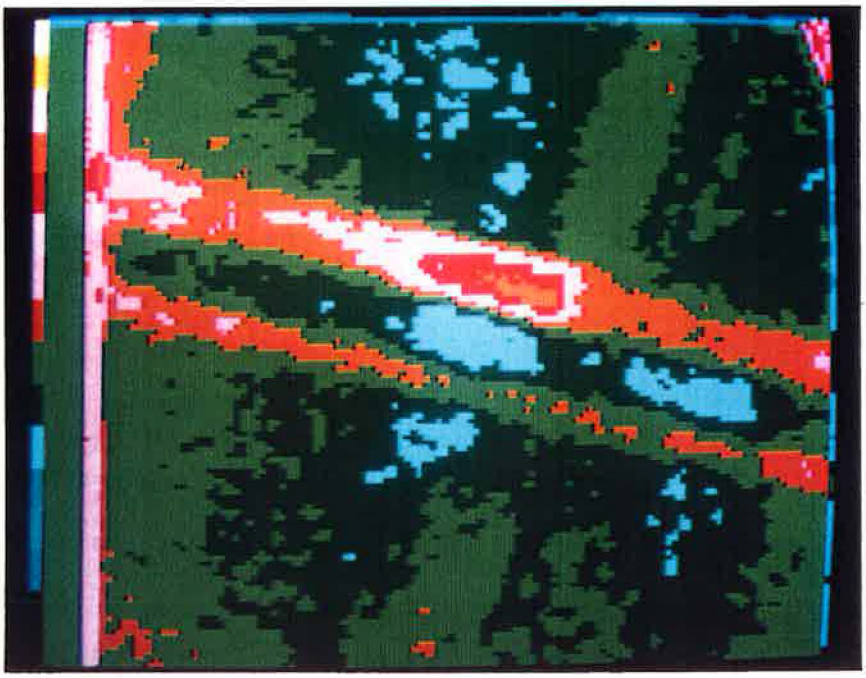


Figure 31(a) Location of an overheating connector block in a high level lighting circuit

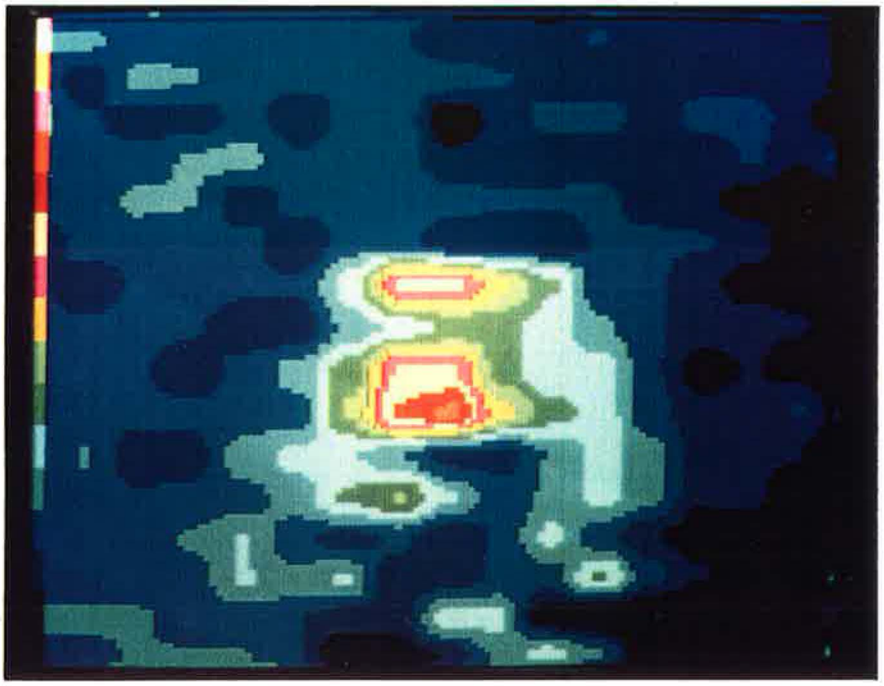


Figure 31(b) As Figure 31(a) but image enhanced close up of connector showing 'hot' spot

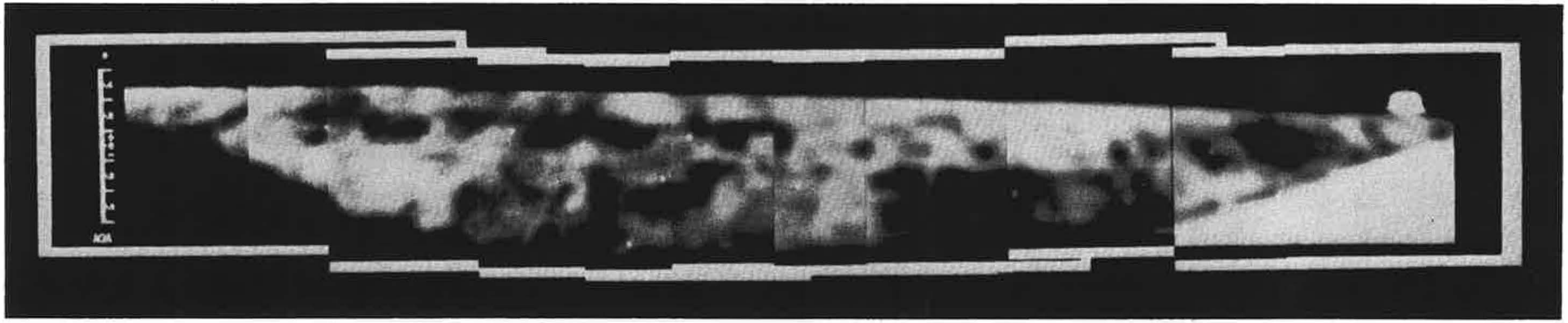


Figure 32 Part of an earth embankment dam showing surface dampness indicated by the dark areas on the down stream slope.

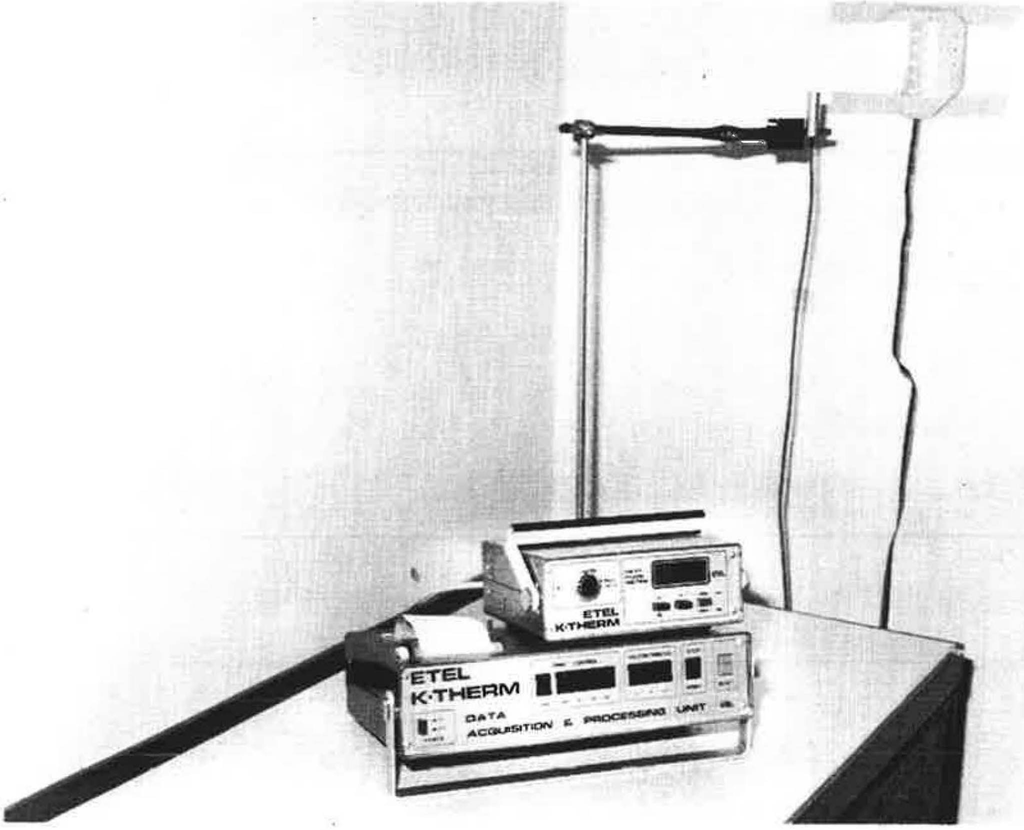


Figure 33 Heat flux plate and monitor unit for in-situ measurement of U-value

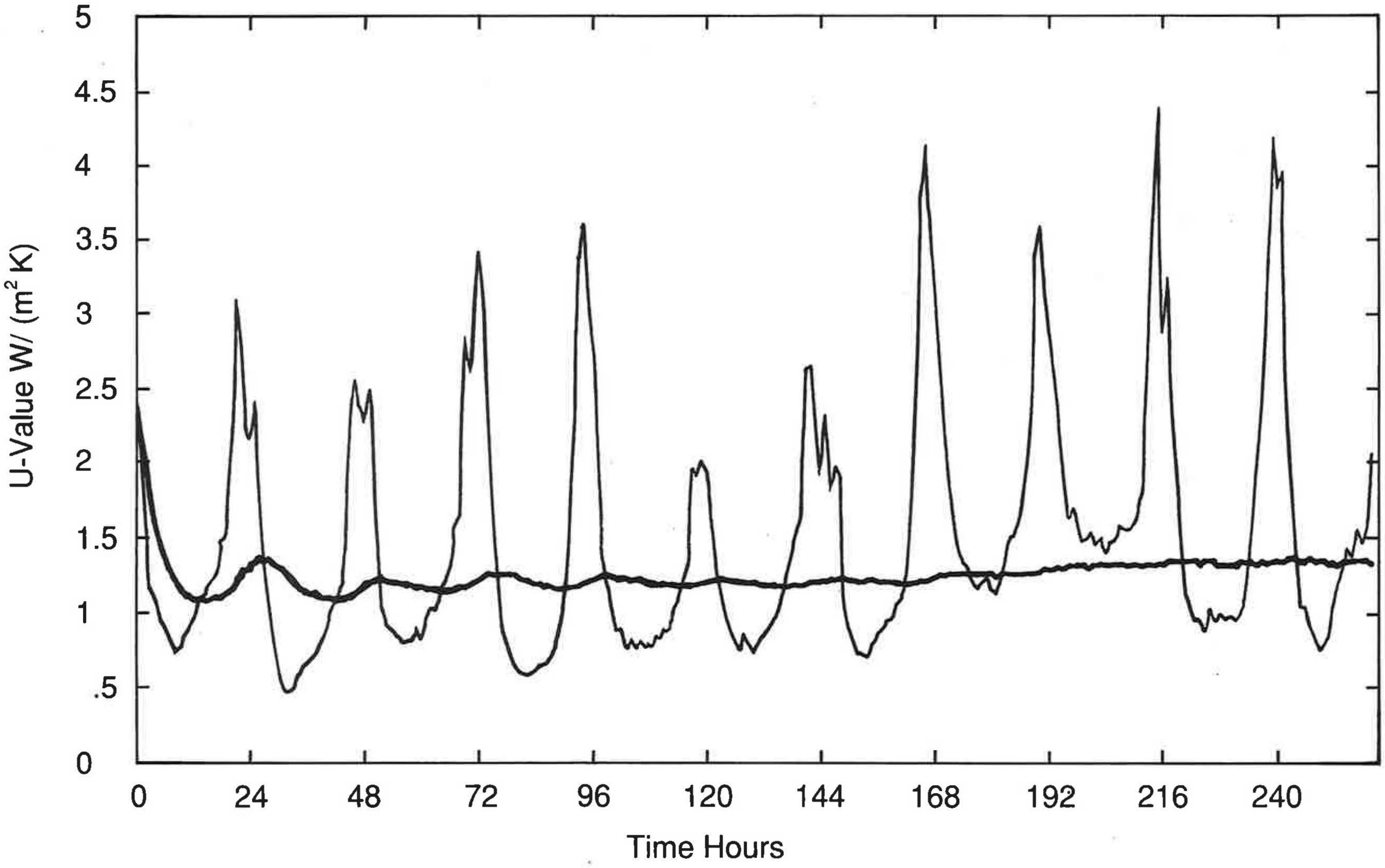


Figure 34 Variation with time of the instantaneous and average U-value for a cavity constructed brick/block wall

Figure 35 Industrial optical probe equipment

Figure 36 Optical probe set up for inspection

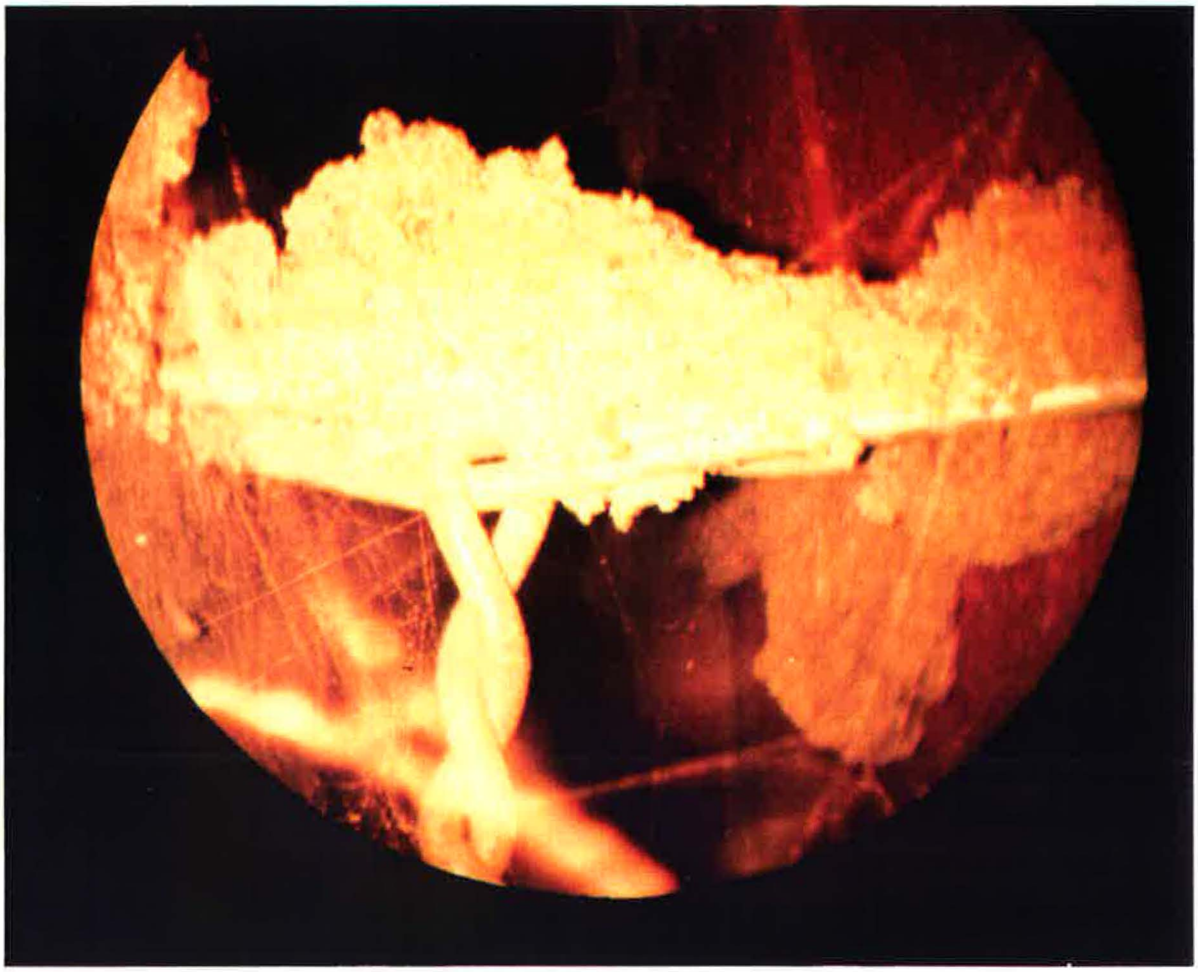


Figure 37 Optical probe photograph showing a mortar 'bridge' resting on a wall tie

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